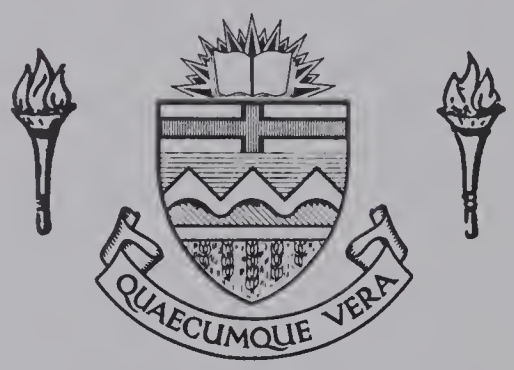

THE UNIVERSITY OF ALBERTA

INTERACTIVE GRAPHICS IN THE REDUCTION OF DATA OBTAINED FROM A GAMMA-RAY CAMERA

by

© JIRI JELINEK

A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled INTERACTIVE GRAPHICS IN THE REDUCTION OF DATA OBTAINED FROM A GAMMA-RAY CAMERA submitted by Jiri Jelinek in partial fulfilment of the requirements for the degree of Master of Science.

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INTRODUCTION

The usefulness of radioactive materials in medical research and clinical diagnosis has been demonstrated over the past 15-20 years. In a practical sense the gamma-ray emitting nuclides have proved of greatest value in clinical studies, particularly in metabolism and organ visulization investigations. This technique, commonly known as "radioisotope scanning", is widely applied in routine clinical diagnosis at the present time. Historically, the first diagnostic application of radiosiotopes in medicine was limited, by instrumentation, to a measurement of "uptake" of the radioactive material in the organ under study. Thyroid gland investigations are a classical example of such a technique. By definition, "uptake" implies gross deposition of the radioactive tracer in the organ under investigation and thus no information concerning distribution of radioactive tracer in the organ is obtained.

Radioisotope scanning methods for organ visualization have been in use since 1951. Rectilinear scanners comprising a Sodium Iodide scintillation crystal, focused collimator (1) and electronic and mechanical equipment, enable studies of distribution of radioactive materials in the organ. In recent years the ready availability of short lived radioactive materials has resulted in almost universal application of rectilinear scanning methods in routine clinical diagnosis of abnormalities in most of the body's organs.

The form of administration of the radioactive material ranges from intravenous and interarterial injections to the administration of

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[1] B. D. Corbett and A. T. Honour, Design of directional counters for clinical use. Nucleonics 9:5, 1951.

liquids or tablets. The half-life of the radioisotope is an important consideration in such investigations as is also the energy of the emitted gamma radiation. The choice of radioactive tracer thus depends upon the particular application. In a practical sense the energy range 100 keV - 500 keV is the most useful for medical purposes. The restrictions are gamma radiation absorption by the tissue on one side and structure of the collimator and safety of the patient on the other.

A short effective half-life of the isotope offers the possibility of repeated investigation, however, this advantage is somewhat offset by increased requirement of speed in the scanning process because of decay of radioisotope during the measurements. Probably the fastest scanner is reported in (2) where a brain scan can be done in 90 seconds.

Rectilinear types of scanner are inadequate in situations where the half-life of the isotope is comparable to the time necessary to cover the area being examined or in situations where dynamic studies are to be undertaken.

In 1958 a new device called the Gamma-ray Camera was introduced by Anger (3, 4). After extensive research, which is well described in (5),

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[2] R. N. Beck, D. B. Charleston, D. Eidelberg, and P. V. Harper, The Argonne Cancer Research Hospital's brain scanning system. J. Nucl. Medicine 5, 1964, pp. 370.

[3] H. O. Anger, Scintillation Camera. Review Scientific Instruments 29:27 1958.

[4] H. O. Anger, Scintillation Camera and Positron Camera. International Atomic Energy Agency, Vienna, Austria, 1959.

[5] N. F. Moody, W. Paul, M. L. Toy, A survey of Medical Gamma-ray Cameras, Proc. IEEE 58:2, February 1970.

the fastest devices of this type can measure radioisotope distributions in body organs in times of the order 1/10 of second (6).

Using such instruments for studies of the radioisotope distribution dynamics inside the human body produces a large amount of radiation counting data. Effective reduction and evaluation of such experimental results can be made only by a large scale digital computer.

This thesis presents a method of data reduction in such experiments using Interactive Graphics, a technique which has prospects for use in routine clinical situations.

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[6] PICKER NUCLEAR, White Plains, N. Y., Publicity Sheet CL1-676009, 1967.

CHAPTER I

THE GAMMA-RAY CAMERA

1.1 Principles of Operation

The gamma camera can be considered as comprising 2 components which are usually separated physically. These are:

a) The gamma-ray detector.

b) The electronic system.

The gamma-ray detector, shown in Fig. 1.1.1, comprises the collimator, the sodium-iodide crystal, the light pipes, the phototube array, and the resistive matrices weighting the outputs from the photomultipliers. A geometrical correspondence between the spatial location of the point of gamma-ray emission (the object) and the point of gamma-ray interaction in the NaI(Tl) crystal is achieved by using an appropriate lead collimator. In other words points on the surface of the crystal can only be reached by gamma rays which originated at corresponding points of the source (object). Interaction between the gamma-ray photons, which pass through the collimator, and atoms of the NaI(Tl) crystal creates many low energy photons (in the visible and ultraviolet range of the spectrum). These photons are routed by the light pipes to a number of phototubes covering the exit surface of the crystal. Anger (7) proposed an arrangement of 19 photomultipliers which could distinguish several hundred picture elements.

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[7] H. O. Anger, The scintillation camera for radioisotope localization. Cnf. on Nuclear Medicine, Heidelberg, October 1966.

High resolution is achieved in the following manner:

The light created by a scintillation is scattered throughout the crystal, however, the output pulse of each photomultiplier is proportional to its relative distance from the source of the scintillation. The position of the scintillation can then be assessed by comparing the relative pulse heights of the photomultiplier outputs. The integration of pulse outputs from all photomultiplier tubes is then used to provide an output signal directly proportional to the incident gamma-ray energy and this pulse is used in the spectrometer energy selection process.

Three separate passive weighting networks are used for the pulse manipulation. Two of these evaluate scintillation positions in an orthogonal (x, y) coordinate system and the third provides the Z pulse, corresponding to gamma-ray energy, to be inputted to a single-channel pulse height analyser for energy selection. Since the positional information is also energy dependent, normalization with respect to the energy pulse is usually done by a fast electronic divider in real time. The principles of gamma-ray detector operation as described above are rather general. The performance of the electronic system of different cameras can, however, vary considerably. Specifications for the particular gamma-ray camera used in our investigations are given below.

1.2 PHO/GAMMA III Scintillation Camera System

The Pho/Gamma III Scintillation Camera* was developed for medical purposes and operates with gamma-ray energies in the range 80 keV to 511 keV, a range which also includes the positron emitting nuclides. Because of the camera's high sensitivity, pictures can be taken very rapidly.

* Nuclear-Chicago Corporation - MODEL 6403

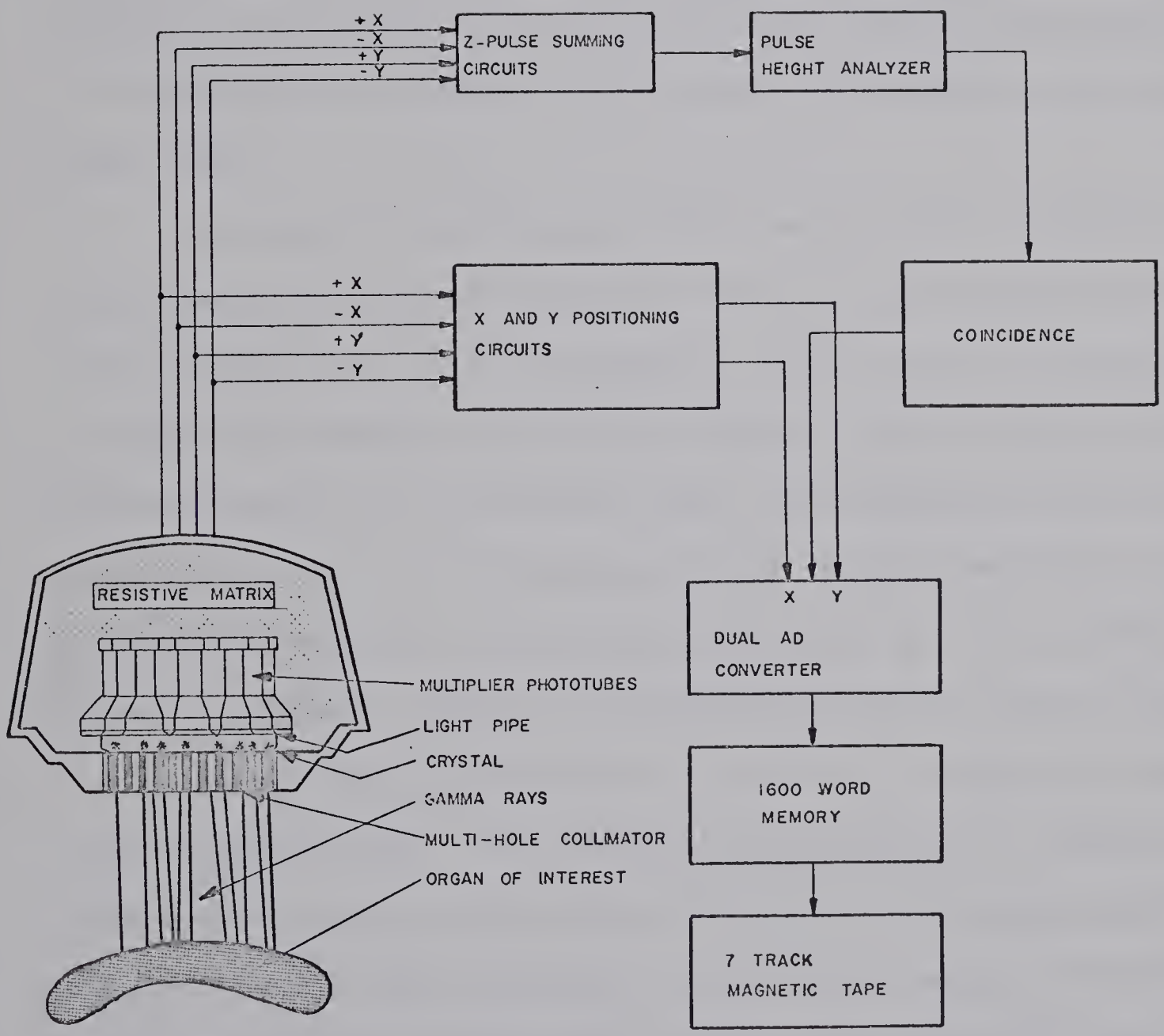

Figure 1.1.1 Block diagram of the analyzer-camera system

Three interchangeable collimators are furnished with the instrument in order to satisfy various sensitivity and resolution requirements. The collimators are of three types, parallel multi-hole, diverging and pin-hole. Further details concerning collimators can be found in reports by N. F. Moody and Nuclear-Chicago Corporation (5, 8).

This thesis is concerned with radioisotope distribution information relating to dynamic processes in internal body organs. Multi-hole parallel and diverging collimators were used to achieve the geometrical correspondence between points on the crystal with points on the organ under study.

Operation of the Pho/gamma III is as described in Section 1.1. Only those gamma-rays travelling in a direction approximately perpendicular to the crystal face are allowed to pass through the collimator's straight-bore openings and strike the crystal. Most of the other gamma-rays are stopped by the collimator septa. The position of the scintillation in the crystal is translated, by the hexagonal multiplier phototube array and the resistive positioning matrix, into ±X, ±Y positioning pulses. A schematic diagram of the detector system is shown at Figure 1.1.1.

In the energy channel the +X, -X, +Y and -Y signals are summed to form a Z-energy pulse. This Z-pulse is then analyzed by a single channel pulse height analyzer to determine if the total input energy generated by the sinctillation event represents the photo-peak energy of the isotope being used. If it satisfies this condition the Z-pulse will pass through the analyzer window to be stored as described in Section 1.3.

---

[8] NUCLEAR-CHICAGO CORPORATION, PHO/Gamma III Scintillation Camera System. Model 6403, 1967.

Before a particular experiment commences the energy analyzer window must be set according to the isotope being used. For this purpose an energy spectrum of Z-pulse signals is displayed on the screen of oscilloscope (Fig. 1.2.1). The actual window used for centering of the photo-peak appears as a blanked out sweep trace and can be adjusted by manual controls.

1.3 Analog data acquisition, analog to digital conversion and digital data storage techniques in dynamic radioisotope function studies.

To be able to evaluate dynamic studies with a digital computer, fast and reliable hardware is required for both A-D conversion of X and Y addressing signals and for information storage prior to transfer to magnetic tape.

We have available a Model 24-3* 1600-word memory. This 1600-24 bit word ferrite core memory is a very flexible device (including even a small data processor) offering a number of features covering most types of radioisotope imaging and counting experiments. These instrumental features are well explained in the operation manual (8) and no attempt will be made to describe them here.

In the following we restrict ourselves to a brief description of digitization of the output data from the gamma-ray camera and the data transfer to tape. A simplified block diagram of the analyzer-camera system is shown in Fig. 1.1.1.

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* Nuclear-Chicago Corporation

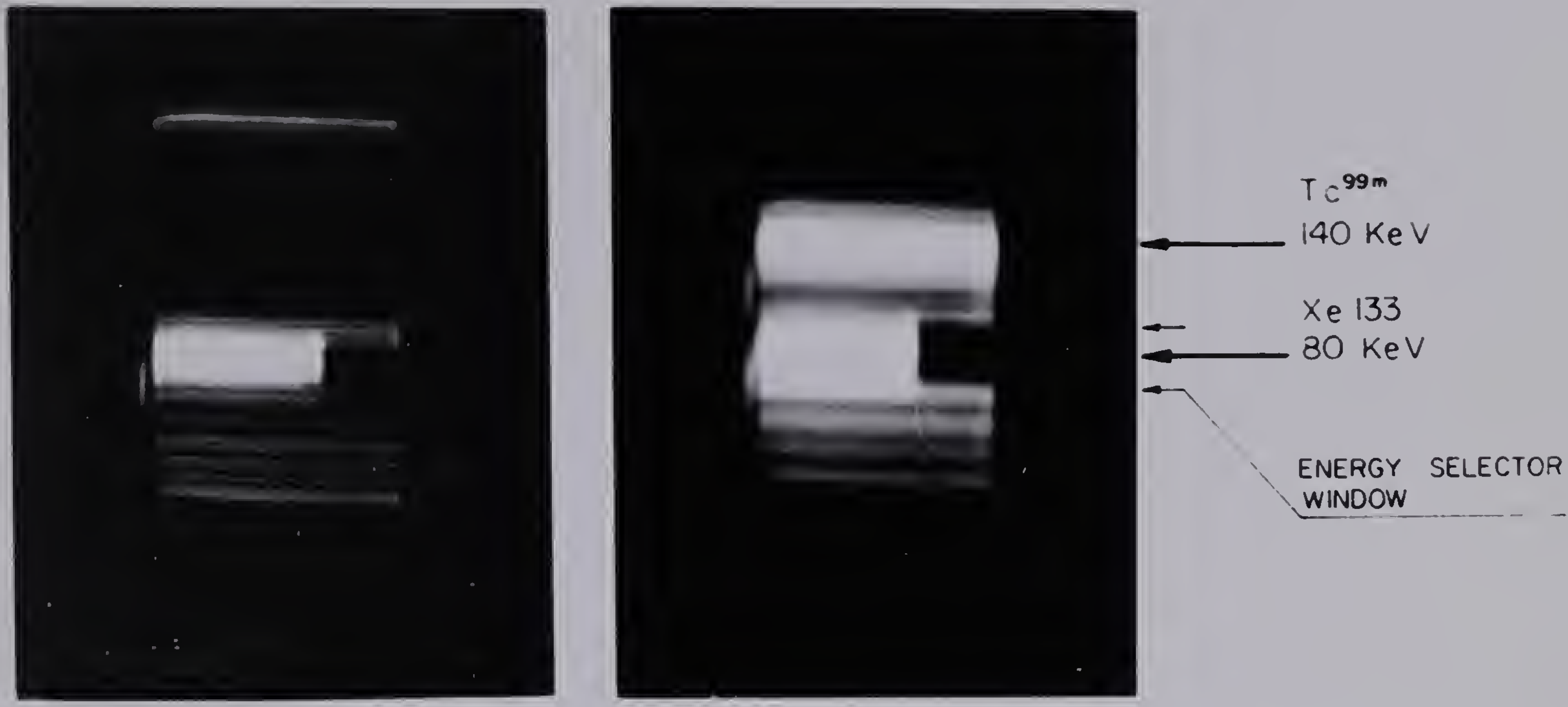

FIG. 1.2.1. DISCRIMINATOR ADJUSTMENT FOR GAMMA-RAY ENERGY

TAG WORD=100607

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0	0	C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	6	6	6	4	3	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	3	4	5	13	8	8	9	11	9	2	4	0	0	0	0	0	0	0	0	0	0	0	0
0	0	C	0	0	0	0	0	0	0	0	1	1	1	5	6	15	17	15	11	8	12	17	21	31	17	9	11	4	0	1	1	0	0	0	0	0	0	C	0
0	0	0	0	0	0	0	0	0	0	0	3	1	10	6	27	23	14	17	11	17	15	24	28	25	15	19	18	22	13	5	1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	4	14	14	12	18	9	14	16	14	17	15	16	16	14	13	14	13	19	17	17	7	3	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	2	7	13	11	22	14	7	22	17	12	17	19	17	8	11	9	13	11	11	15	18	14	15	3	1	1	0	0	0	0	0
0	0	0	0	0	0	0	0	1	10	8	9	16	9	9	11	18	15	18	20	14	15	16	11	11	12	19	23	20	14	26	15	7	4	0	0	0	0	0	0
0	0	0	0	0	0	1	1	3	6	6	9	13	16	17	11	13	27	27	16	15	18	12	23	30	18	22	12	9	13	15	12	13	4	6	0	0	0	0	0
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0	0	0	0	0	0	1	7	3	8	11	5	10	12	12	18	23	21	29	19	19	22	23	24	29	31	29	15	13	9	14	8	5	11	6	5	2	0	0	0
0	0	0	0	1	0	3	4	5	7	13	7	16	14	12	18	20	25	22	32	24	21	22	41	27	23	17	10	11	14	15	9	7	9	5	7	2	0	0	0
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0	0	0	0	0	3	4	4	8	9	9	8	13	13	20	17	18	16	18	20	14	19	22	12	37	28	28	25	13	12	6	10	3	7	7	7	2	1	C	0
0	0	0	0	2	2	4	3	9	9	13	6	11	16	13	14	19	14	28	24	26	12	14	31	31	32	23	16	10	10	9	12	5	4	3	6	8	2	C	0
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0	0	0	0	0	2	5	6	2	7	10	5	9	6	11	7	5	19	26	41	15	32	22	25	10	9	8	8	3	4	6	3	7	3	7	1	5	2	1	0
0	0	0	0	0	5	5	2	3	4	4	5	6	4	4	6	5	6	9	24	13	17	23	15	8	3	8	6	6	3	5	9	3	4	6	1	3	1	0	0
0	0	0	0	0	2	5	5	1	0	5	4	4	11	5	5	6	4	12	11	12	12	9	8	10	6	1	4	2	4	3	1	4	5	2	3	6	0	0	0
0	0	0	1	2	1	1	1	3	4	3	5	2	1	3	0	5	7	5	10	4	2	1	6	5	2	3	3	3	1	0	3	8	1	4	2	1	1	0	0
0	0	0	0	1	3	1	5	3	2	3	0	4	2	0	6	4	5	4	2	3	1	3	3	6	5	2	4	2	3	2	2	0	3	2	2	1	0	1	0
0	0	0	0	0	0	0	1	2	5	0	0	1	1	8	1	3	0	4	2	2	2	5	3	4	4	5	1	2	2	1	0	1	2	2	0	1	1	0	0
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0	0	0	0	0	0	0	0	2	1	2	0	3	3	0	2	1	5	4	0	2	0	2	3	1	0	1	1	1	1	1	0	3	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	1	2	1	1	1	2	2	1	1	1	2	0	1	1	1	1	3	3	1	0	0	0	1	2	1	0	0	0	0	0	0	0
0	0	C	0	0	0	0	0	0	1	1	1	1	2	1	0	1	0	1	0	1	1	1	1	2	2	0	0	3	2	0	1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	1	1	0	1	1	2	1	3	0	1	1	2	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	2	2	1	0	0	0	2	0	2	2	2	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	2	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

```
DISPMX(   16    3    6)
MAXCNT=      41
BLOCK(111)
CNTLEV=       6
CNTLEV=       8
CNTLEV=      10
JC=   14
IVCTCT=    251
                       ENDAY-ITW,IAV,IERR,NBLK:        6        6        0        90
                       INOUT READ-ITW=   100605
```

FIG. 1.2.2. EXAMPLE OF GAMMA-CAMERA OUTPUT DATA IN DIGITAL FORM (40 x 40 MATRIX)

PHA store operation (or pulse height analysis) is used to accumulate the number of Z pulses, satisfying selection criteria, within a period of time adjusted according to particular experimental requirements. Storage in the Model 24-3 consists of locating a selected address in the ferrite core memory, extracting the number of counts previously held in the selected group of cores and incrementing this count total by one each time the address is selected. The maximum number that can be stored in one channel of the memory is 10^6.

For our particular applications which are concerned with the distribution of a radioisotope over some (projected) area, the 40 x 40, X - Y addressing format was used. The location X = 0, Y = 0 was reserved for counting the output (.01 min. pulses) from the timer system.

A magnetic tape system* was used for recording data which has been collected by the analyzer system. This system comprises a controller, an interface and a 7-track tape transport unit;** thus providing facilities for the data transfer between the analyzer and the digital computer. The operation of the system is well explained in the appropriate manual (9). In following we briefly describe some characteristic features.

Before a data set is written for transfer to the computer a data format, record length, parity, coding, density of the record, etc. must

* Nuclear-Chicago Computer Compatible Magnetic Tape System Model 24201.

** Hewlett-Packard 2020 Digital-Tape Unit.

---

[9] NUCLEAR-CHICAGO CORPORATION, System Operation for Models 24201, 24202, 24203, 24204 Magnetic Tape Systems, 1968.

be set to satisfy the requirements of the particular computer system. The following compatibility requirements can be set in the controller:

1) Number of characters (2 - 6) per data word
2) BCD sign designation
3) Maximum record length
4) File mark function
5) Tag word function

In most cases the data word to be recorded will contain the count being stored in some memory channel. The maximum value of the count for given experiment varies considerably; being in the range of few counts up to 10^6. To minimize the actual transfer time for data characters as few characters per data word as possible should be used.

When a sign designation is necessary, it may be either a sign character preceding the data characters in each word, or it may be achieved by modification of the lowest order character. In the experiments described in this thesis all data were considered as positive numbers and there was no need for the sign designation.

The maximum record length is given by the number of data words (channels) to be recorded and by the number of characters per data word. For the 40 x 40 addressing scheme all 1600 channels were recorded with 3 characters per word during the lung measurements and 4 characters per word during the pancreas - liver studies. An additional 6 characters were required for the tag word. Descriptions of the experiments mentioned above can be found in the following chapter.

To achieve a low total transfer time all 1600 words were recorded as one block with the size equal to the logical record length (4806 and 6406 for 3 and 4 characters per word respectively), which

minimized number of inter-record gaps. Such an arrangement resulted in a total transfer time of approximately 300 ms, 400 ms and 890 ms for densities 800 bpi, 556 bpi and 200 bpi respectively.

The file mark function of the Nuclear-Chicago Magnetic Tape System is not compatible with that of the IBM 360/67 system. For this reason a file mark was written on the tape only following the last data set recorded in order that this point could be located when additional data needed to be written on the tape. This file mark is erased when the new data is recorded.

The first word of each data set - the tag word - is used to provide the data set identification. It has the standard format of six BCD digits. During the measurements of radioisotope distribution dynamics the control logic and time circuits of the analyzer provided for automatic data collection and memory dumps to tape. The controller logic automatically increments the preset value of the tag word before it is recorded as the identification of the following data set. The parity of each recorded character is checked by read-after-write circuitry and each error increments the error counter included in the controller.

CHAPTER II

EXPERIMENTAL METHODS AND DATA REDUCTION REQUIREMENTS

The data reduction method using Interactive Graphics which is described in this thesis was developed according to the requirements of several experimental studies carried out in the Division of Biomedical Engineering. These investigations include:

1) Experimental evaluation of regional pulmonary blood flow in dogs after lung transplantation; an investigation conducted by Dr. T. R. Overton and Dr. P. G. Heslip (Division of Biomedical Engineering, Faculty of Medicine) and Dr. R. L. Fisk (Surgical - Medical Research Institute).

2) An evaluation of changes in regional pulmonary perfusion in humans in response to various administered drugs. This study was conducted by Dr. D. Shaw (Division of Pulmonary Diseases) and Dr. T. R. Overton.

3) Experiments related to digital image subtraction methods in pancreas visualization recently carried out by Dr. T. R. Overton and Dr. P. G. Heslip.

From the point of view of methodology for data reduction and analysis both pulmonary perfusion experiments are very similar. We shall illustrate typical experimental methods associated with the studies of radioisotope distribution dynamics by a description of the study of regional pulmonary perfusion in humans. This study is reported in (10).

---

[10] T. R. Overton, D. Shaw, L. Friedenberg, B. J. Sproule, and J. Jelinek, Regional pulmonary blood flow: A quantitative study using a digital computer for the reduction of gamma camera "images" produced using Tc^{99m}. To be published.

To be able to simultaneously measure the distribution of radioisotope "tracer" in both lung fields the diverging collimator was used with the gamma camera. After the injection of Technetium 99m via the left anticubital vein the course of its distribution was measured by the gamma camera. During one cycle of measurement the counting rate distribution information was accumulated in the core memory of the analyzer for a time period of 600 ms and then dumped as one block on 7-track tape. (The procedure was described in Section 1.3.) We shall call this data block the "matrix" in the following discussion. The dumping of 1600 channels of memory required about 300 ms. During this time interval the counting rate distribution information as detected by the gamma camera was lost. Such a cycle of measurement lasts 1 second and about 50 matrices were repeatedly obtained on each experimental subject. Data recording was stopped after "wash-out" of radioisotope from lung fields when the recirculation of radioisotope was observed on the oscilloscope screen of the analyzer. This procedure was then repeated after the administration of drugs (Isuprel or Adrenalin) to enable the evaluation of their influence on lung perfusion.

To avoid erroneous evaluation of experimental data, analysis has to be restricted only to the matrices being obtained during the pulmonary transit time before recirculation of the radioisotope. In terms of the series of matrices we shall refer to this time interval as to the "range of interest". Since the range of interest is usually different for each subject, it is necessary to compute a pulmonary transit time curve (the time course of total response computed over each matrix of the series) to be able to specify this range.

Furthermore, it was found that, particularly in the range of interest, the data obtained in the area of heart and radioisotope inflow comprise a substantial part of the total response computed over the matrix. The matrix elements which represent the count information from such areas have to be made zero and excluded from further data analysis. According to the common medical terminology we shall call this process the "subtraction of area" in the following discussion. The assumption can be made that the location of subject's organs under the gamma camera is the same during the measurement of the matrix series.

The data analysis methods include a number of various numerical procedures, the considerations above, however, have rather general character. From the point of view of Interactive Graphics the basic requirements for reduction and analysis of data obtained in studies of radioisotope distribution dynamics can be summarised as follows:

1) to define the range of interest in the matrix series which is relevant for further data evaluation,

2) to define the area on the matrix (common for all matrices of series) to be excluded from further analysis,

and 3) to define the subdivision of the matrix into a number of compartments according to the particular data analysis techniques employed.

In experiments concerned with the pancreas visualization only stationary distributions of the radioisotope were measured and for this reason, from the three requirements above, only the specification of an area of interest on the matrix was involved. A report on this study is given in (11). The use of Interactive Graphics in an experimental

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[11] T.R. Overton, P.G. Heslip, P.A. Barrow and J. Jelinek, Dual radioisotope techniques and digital image subtraction methods in pancreas visualization. To be published.

evaluation of regional pulmonary blood flow in dogs after lung transplantation is reported in (12).

The data reduction subroutine package which provides the necessary functions to facilitate the general data reduction requirements is described in Chapters IV and V.

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[12] J. Jelinek, Interactive processing of gamma camera pictures using a graphical display subsystem. University of Alberta Computing Review 3, 1970, pp. 78-91.

CHAPTER III

GRAPHICAL DISPLAY SUBSYSTEM

On the basis of the data reduction requirements described in the previous chapter an interactive program was implemented on the IBM 360/67 computer and CDC Graphical Remote Interactive Display currently available at the University of Alberta. Some features of the hardware and software are described below.

3.1 CDC Graphical Remote Interactive Display (GRID)

GRID comprises a controller, a monitor, an operator panel, alphanumeric and function keyboards, and a power unit. A schematic diagram of the device is shown in Figure 3.1.

The communication between the 360/67 and the controller is provided through an interface and local compatible modem and is under the control of the 360/67 executive program.

There are two modes of operation within the subsystem - the display mode and the processor mode - which share the same arithmetic and memory circuitry. The mode of operation can be defined by the 360/67 or can be selected by the operator at the terminal.

The processor of the subsystem operates only during the processor mode. It executes the instructions necessary for communication with the 360/67, handles interrupts and the processing required for modification of the picture being displayed. It has complete store accessing and can execute a wide variety of instructions as additions, subtractions, shifts, logical instructions, jumps, etc.

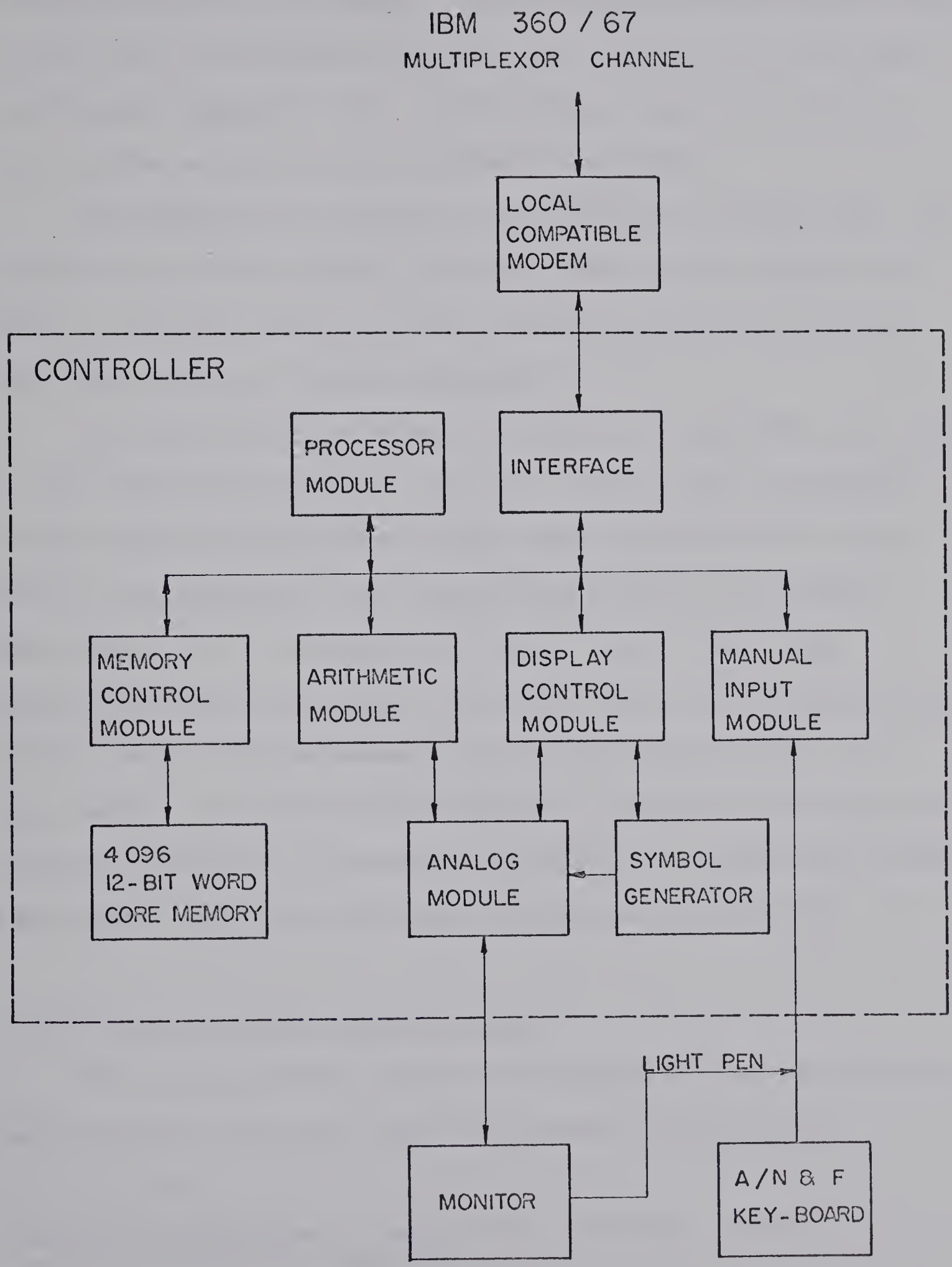

Figure 3.1 Schematic diagram of CDC Graphical Remote Interactive Display (GRID)

The fixed point arithmetic facility for both operational modes is provided by the arithmetic module. In the display mode it is used to compute the X and Y coordinates for absolute and relative beam positioning, vector length computation, etc. In the processor mode the arithmetic module carries out all processor arithmetic operations.

The display control module is active during the display mode. It provides the circuitry enabling use of the words from the display file stored in the memory module, and their decoding, to control the operation of the analog and arithmetic modules.

The main part of the terminal is the 12-inch square CRT with 1,024 by 1,024 addressible locations. Any point, vector, symbol or subpicture on the screen can be detected by a light pen provided that the detectibility is not inhibited. After the light pen detection an automatic change from display to processor mode occurs. The processor then generally determines the source of interrupt, identifies the object being detected, executes the corresponding routine and switches back to the display mode. The behavior of the terminal in response to the light pen, function or alphanumeric interrupts is defined by the "supervisor" in the memory module. More information about GRID can be found in (13).

3.2 IBM 360/GRID Graphics Software System

The Graphics software system (14), developed in the Department of Computing Science during the last year comprises four main parts:

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[13] Control Data Corporation, Graphic Display Subsystem. Volume A - Technical, DD1-TD-7051, March 1968.

[14] F.B. Jacobsen, K. F. May, W.H. Huen, J.P. Penny, Computer Graphics for the Fortran programmer. University of Alberta Computing Center publication, 1970.

1) The Graphics Master Control Routine,

2) the General-purpose supervisor,

3) the Input-Output routines,

and 4) the Graphics support subroutines.

The Graphics Master Control Routine (MCR) acts as a main control for graphics application programs. It establishes the communication of the 360/67 with GRID, transmits the input-output routines (and also those routines called by application programs) from the graphics library into the 360/67 core and loads the general-purpose supervisor into the GRID memory. The application program is then executed as a subroutine of MCR.

The supervisor essentially defines the behavior of the display terminal by handling the interrupt information from the display unit. Its function consists of assembling a message for the 360/67 on the basis of the actions taken by the terminal operator. The message, after transmission to the 360/67 and decoding, then provides the necessary information for further execution of the application program.

To avoid the use of GRID processor machine code in the applications programs a package of FORTRAN routines was written (15). These enabled interactive control of GRID by means of subroutine calls.

Data to be displayed are divided into a number of BLOCKS constructed from the basic picture elements such as points, line segments and symbols. It is assumed that each BLOCK corresponds to some characteristic pattern of the data (at the discretion of the programmer) and, during the light pen interrupt, the identification of the BLOCK being

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[15] W.H. Huen, A Fortran graphical subroutine package. University of Alberta Computing Review 2, pp. 58-79, 1969.

pointed to is important information to be used by the application program. Blocks are identified by integer numbers rather than by symbolic names.

It is usually convenient to define more blocks than are being displayed at a given time (e.g. to define also error messages which are occasionally displayed). For this reason two files are kept in the 360/67 core memory: BLOCK FILE and DISPLAY FILE.

The block file contains the specifications of all blocks defined while the display file contains only the specifications of the block being displayed. A copy of the display file is also kept in the core memory of the GRID and it is created or changed by the GRID processor on the basis of the messages from the 360/67.

In general the structure of an application program comprises the following components:

a) BLOCK definitions,

b) display requests,

c) transmission of the message between the 360/67 and GRID,

d) message-decoding statements,

e) statements being executed in response to action of the terminal operator. These statements also comprise BLOCK definitions and deletions which are, by display requests, assembled into the display file in the 360/67. The corresponding changes in the GRID core display file are made after the message transmission.

After the application program transmits the picture changes, its execution is stopped until the next message from GRID is recieved. During this relatively long waiting period the 360/67 time sharing system executes other tasks in the system. The message from GRID contains the

sources of interrupts (i.e. light pen, alphanumeric keyboard or function keyboard) and the information pertaining to them (i.e. identification of the block being picked, character string typed or code corresponding to the particular function key used).

CHAPTER IV

INTERACTIVE REDUCTION OF DATA OBTAINED IN STUDIES OF RADIOISOTOPE DISTRIBUTION DYNAMICS

4.1 DRISP - The Data Reduction Interactive Subroutine Package

In order to satisfy the data reduction requirements, the following features had to be implemented:

1) Data transfer, storage and retrieval.
2) A graphical representation of the radioisotope distribution and a method of display modification.
3) The specification on the graphical representation of an area of interest or subdivision.
4) The specification of a range of interest in a series of matrices.
5) Performing some arithmetic operation on each matrix of the series from a range specified in 4.
6) The method of results presentation.

Let us briefly mention some considerations taken into account when corresponding subroutines were being written.

To satisfy the wide range of requirements, necessitated by the variety of possible experiments to be evaluated an attempt was made to write the subroutines in as general and flexible a manner as possible. The important features of the subroutines usually depend on particular parameters which can be changed by recompiling of the routines.

An origin, size and complexity of the graphs and graphical representation of the matrix, the amount of working space on discs, etc. are typical examples of such features. For some experiments however, in

addition to possible parameter change, it is necessary to supply additional subroutines to satisfy requirements. For example, the routines dealing with the subdivision of the matrix into a number of compartments will, most probably, have to be written specially for a particular application. In the majority of cases different input-output statements will be required. For this reason separate input-output routines, READT and INOUT, were written enabling easy modification of the data transfer.

At the beginning of a session the display of the Decision Table is presented, which allows the user to select one of six basic options:

1) transfer a specified number of records (matrices) from the tape into the direct access disc,
2) perform functions associated with the matrix display and the boundary or subdivision specification,
3) display the Boundary Options Table,
4) specify the series to be evaluated and display graph-integrals over the matrices of the series against the corresponding tag words,
5) evaluate compartments of matrix subdivision for a specified series of matrices,
6) terminate session.

Copies of the Decision Table and Boundary Options Table are shown on Figure A.1 and Figure A.2 in the Appendix.

The meaning of entries in the Decision Table and Boundary Options Table will be explained in Section 4.4 where the specification of the command language is given.

We shall discuss, in detail, only the graphical representation of the radioisotope distribution (Section 4.2) and the boundary and subdivision definition and decoding (Section 4.3).

The complete list of the routines is given in Table 4.1.1 (FORTRAN routines) and in Table 4.1.2 (IBM 360 Assembler Language). Columns of the tables contain an identification number for the subroutine, its name, number of bytes occupied by the subroutine (in hexadecimal form) together with identification numbers of the subroutines called by the given subroutine, and a function of the subroutine respectively. The tables can be better understood after reading Sections 4.2, 4.3 and 4.4.

TABLE 4.1.1

ID	ROUTINE NAME	LENGTH [ROUTINES CALLED]	FUNCTION
0	GRIDSUB		Graphics support subroutines
1	GRAPHIC	D58 [0, 2, 3, 4, 8, 14, 19, 20]	(This routine is included in MCR and contains the main application program) - defines and displays a Decision Table - supplies the logic related to the Decision Table
2	DDTAB	1EE [0]	- displays the Decision Table
3	EDTAB	18E [0]	- erases the Decision Table
4	READT	1272 [0, 5]	- finds specified series of matrices on the tape - writes specified number of blocks on discs
5	TWLIST	F54	- read a disc file and create the list of tag words and corresponding associated variables in the 360 core
6	INOUT	23C	- read/write the matrix specified from/on disc
7	GETAVR	204 [25, 29]	- finds the range of the associated variables corresponding to a tag word range
8	MDISP	1C56 [0, 9, 10, 11, 12, 13, 28, 29]	- facilitates the picture generation and modification - enables specification of the boundary or subdivision
9	DELBLF	1C0 [0]	- deletes the superfluous blocks from the BLOCK FILE before the picture is generated

ID	ROUTINE NAME	LENGTH [ROUTINES CALLED]	FUNCTION
10	FNDMAX	1C4	- finds maximum count on the matrix
11	DISPMX	99E [0, 10, 12]	- generates the sequence of the lines creating the picture according to the specified Display Parameters
12	VBVE	36E [0]	- computes the coordinates of the starting and end points of the horizontal lines for one matrix row
13	RSTBLF	6BA [0]	- defines blocks deleted by routine DELBLF from the BLOCK FILE
14	BSUBT	7EA [0, 15, 16, 17, 18]	- defines the blocks of the Boundary Options Table - supplies necessary logic
15	DBSUBT	20C [0]	- displays the Boundary Options Table
16	BSUB	7EA [6, 26, 27]	- subtracts from each matrix of the series the elements w[i, j] located outside or inside of the boundary - stores resulting matrices on discs
17	BINT	5C2 [6, 25, 27]	- for each matrix of the series, integrates w[i, j] located inside or outside the boundary. - displays the graph: integrals against corresponding tag words
18	EBSUBT	1D4 [0]	- deletes the Boundary Options Table
19	SERINT	320 [6, 21]	- integrates each matrix of the series - displays the normalized graph: integrals against corresponding tag words

ID	ROUTINE NAME	LENGTH [ROUTINES CALLED]	FUNCTION
20	SBDINT	5CA [6, 21]	- integrates, separately, each compartment of the matrix subdivision - displays the normalized graphs
21	GRAPH	D9A [0, 22]	- displays one or two graphs - enables the specification of the graphs from A/N keyboard - enables the range of interest specification by LIGHT PEN
22	LPPLOT	994 [23, 24]	- produces a copy of the graphs on the line printer
23	NORM	400	- normalizes values of integrals to be displayed by GRAPH
24	AVRCNT	36C	- integrates the graphs over the specified range
25	FNDAV	254 [0]	- finds the associated variable corresponding to the specified tag word
26	BNDIND	7E0	- finds [i, j] nodes located closest to the boundary
27	SUBINT	4DC	- subtract or integrate the matrix inside or outside of the boundary using specification by BNDIND

TABLE 4.1.2

ID	ROUTINE NAME	LENGTH [ROUTINES CALLED]	FUNCTION
28	ITCTW	48	- convert STRING1, e.g. tag word, from binary to character form
29	CTITW	40	- convert STRING1 from character to to binary form
30	CTITWR	60	- convert STRING 3, e.g. tag word range, from character to binary form
31	CTI	10C	- convert the block of 9600 characters (the matrix) to block of 1600-32 bit binary words

4.2 Graphical Representation of the Radioisotope Distribution

4.2.1 Definition of the problem

The problem can be stated as follows:

Given values of a two-variable function $w = w(x, y)$ at the nodes $[i, j]$ of a rectangular grid, we want to display a matrix $||w[i, j]||$.

Furthermore, boundary definition and display of some areas of interest $w[i, j] \geq C_k$, where C_k is some predetermined level of response ($k = 1, 2...n$), should be possible. Levels of response (counts) C_k can be based upon the percentages of peak response or of total response over the matrix. From the standpoint of interpretation the first technique is better and is used in the present work. Definition of a boundary on a three-dimensional image would be considerably more difficult and is not considered in the present report.

The 2-dimensional representation problem is usually solved by an isocount contour map or by using different symbols or dot desities for different levels of response. Neither of the above methods is particularly convenient for use with GRID, for two main reasons:

1) The complete file to be displayed must be held in the core of the subsystem. At the present time only one memory bank of 4096-12 bit words is available and approximately 1500 words are occupied by the supervisor.

2) To get a constant picture intensity regardless of the number of objects displayed on the screen, the time necessary for display logic should not exceed the period of the refresh cycle (20 ms).

For even simple images, implemented on the basis of the above methods, the above factors would present a considerable challenge to the

present system.

Considering the above noted hardware limitations and following the analysis given in the next paragraph, we chose a horizontal line segment as the basic picture element. For simplicity we shall call the horizontal line segment "the line".

The implications of our choice of display element from a core requirement point of view will be discussed in the next section.

4.2.2 Horizontal line segment as a basic element of graphical representation

Let us first consider the following GRID Assembler Language details.

Suppose that the beam was moved to the starting coordinates of the line, then the display on the screen of the horizontal line with the length $\Delta x < 30$ requires three words (depending on line length, up to 3 additional words could be required) in the core memory of GRID. The first of these enters the vector mode, the second and third are (absolute or relative) position words.

This is the same amount of core used for the display of a point or a symbol. One line, however, can represent the sequence of the elements w[i, j] (with respect to index j) of the matrix row having values inside the lowest range to be displayed.

In order to discuss the problems associated with vector generation let us define following notation:

( ) - denotes a point in the (x, y) coordinate system

[ ] - denotes the NODE of the grid

n - the predetermined number of response levels C_k (k = 0, 1, 2...n)

R_k - the range of the response,

$R_k = \{w[i, j] \;/\; C_{k-1} \leq w[i, j] < C_k\}$; $(k = 1, 2, \ldots m)$*

m - the number of the ranges to be distinguished on the screen ($m \leq n$)

x_j - x coordinate of the [i, j] node

y_i - y coordinate of the [i, j] node

(The x, y coordinate system corresponds to the coordinate system of the GRID screen)

σ - the increment $\sigma = x_{j+1} - x_j = y_i - y_{i+1}$

(A matrix $||w[i, j]||$ with the conventional assignment of subscripts is located in the first quadrant. See Figure 4.3.1.)

kl - the subscript of the lowest range to be displayed.

Let us now assign to the given range R_k of the response, where $k \geq kl$, the density N_r of the lines per matrix row ($r = 1, 2, \ldots m$). The following convention defines the area for generation of lines corresponding to the matrix element w[i, j]:

Each node [i, j] effectively represents the area a[i, j] where $a[i, j] = \{(x, y) \mid x_i \leq x < x_{i+1},\ y_k + \sigma/2 \leq y < y_i - \sigma/2\}$ (as is shown in the example and corresponding Figure 4.2.3.2 in Section 4.2.3). Then, for $N_1 = 1$, one vector will represent the sequence of the elements w[i, j] (with respect to index j) of the particular matrix row having values inside the lowest displayed range R_{kl}.

* The notation defines R_k as the set of matrix elements w[i, j] satisfying the inequality $C_{k-1} \leq w[i, j] < C_k$. This notation is used in a similar sense for definitions of other notions in this chapter.

For practical situations, part of the sequence usually belongs to one or more higher ranges R_k which are also to be displayed ($k \leq k1 + m - 1$). A considerable decrease in the amount of core required to display these subsequences can be then achieved by generation of additional lines in such a manner that:

1) the lines generated to display the lower ranges will continue over the areas of the higher response level, or more precisely, if the sequence of matrix row elements being represented by the density of lines N_a contains the subsequence with corresponding density N_b where $N_b > N_a$, then only the additional $N_b - N_a$ lines will be generated,
2) spacing of the lines in the i (or y) direction is equal inside the area A_k where $A_k = \{a[i, j] \mid C_{k-1} \leq w[i, j] < C_k, k1 \leq k\}$ i. e. where all elements w[i, j] have values in the same range R_k which is to be displayed or in the case $k = k1 + m - 1$ (subscript of the highest range to be displayed) the area A_k can also contain all areas a[i, j] for which the corresponding w[i, j] belongs to all higher ranges defined.

Taking into account the fact that the present goal of graphical representation of the radioisotope distribution w(x, y) is the specification of some area of interest by the light pen, good resolution of a relatively low number of ranges is required. We thus define the density of lines per matrix row as:

$$N_r = 2^{r-1} \; ; \quad r = 1, 2, \ldots m.$$

In applications where display of a higher number of activity ranges would be required the exponential growth of line density could

cause considerable problems. In such cases a different technique for image element definition would have to be used.

In the experiments described in Chapter II, however, the line density function given above resulted in good resolution provided that appropriate parameters n, m and kl were chosen. Notation used in this section will be better understood in the simple example at the end of Section 4.2.3.

The example together with the corresponding Figure 4.2.3.2 will also demonstrate how the conditions imposed on line generation were satisfied. Such values of the matrix elements w[i, j] were chosen so that the corresponding sequence of the horizontal line segments on Figure 4.2.3.2 represented part of the "gray scale" based on the described graphical representation of matrix||w[i, j]||.

4.2.3 Programming considerations for optimal picture generation

The requirement (1) in the previous section is relevant particularily in the case of a radioisotope distribution where the function w(x, y) is expected to be monotonic over most of the region where it is defined. However, local sharp extremes of the function w[i, j], caused for example by the background radiation or by gamma camera performance, can be present.

The error element in the matrix row will cause either the interruption of the lines generated or, in case that its value falls in a higher range, generation of short line segments. In both cases additional core is required and the quality of the graphical representation is decreased. To avoid this image degradation, application of some averaging or smoothing routine is desirable before the display. (Sources of error in gamma camera output data are discussed in Chapter VI.)

In Section 4.2.2 we considered core requirements for the horizontal line segment display with the requirement that the beam was already moved to the beginning of the line. The method described for matrix ||w[i, j]|| representation obviously requires, for each line to be displayed, additional instructions which will move the beam to the beginning of the next line to be displayed. GRID core requirements to accommodate such instructions are comparable with that required for display of the line and again it depends upon the distance which the beam is to be moved. To optimize the line generation a method which ensures a relatively short invisible trajectory of the beam for any possible ||w[i, j]|| should be used. One way to achieve this is shown in Figure 4.2.3.1, where the matrix elements w[i,j], w[i, j+1], w[i, j+2]are represented by the line densities per matrix row N_4 = 8, N_5 = 16, and N_4 = 8 respectively. The arrows show the invisible part of beam trajectory.

During display of experimental data stored on tape it was difficult to predict whether the system limits would be exceeded. It was possible, however, to limit the number of the lines generated but it was difficult to predict their geometrical distribution, the second important factor determining the core required. For these reasons the maximum number of the ranges being distinguished on the screen had to be rather small (m = 8).

There is another factor which limits the complexity of the picture - the size of the picture on the screen. Let us suppose that, in regions of the picture where there is maximum density of lines, all addressable screen points are displayed. To be able to display N_m lines representing the elements of a matrix row from the highest displayed range (or greater) for e.g. m = 8, the size of the picture, which represents the 40 x 40 matrix,

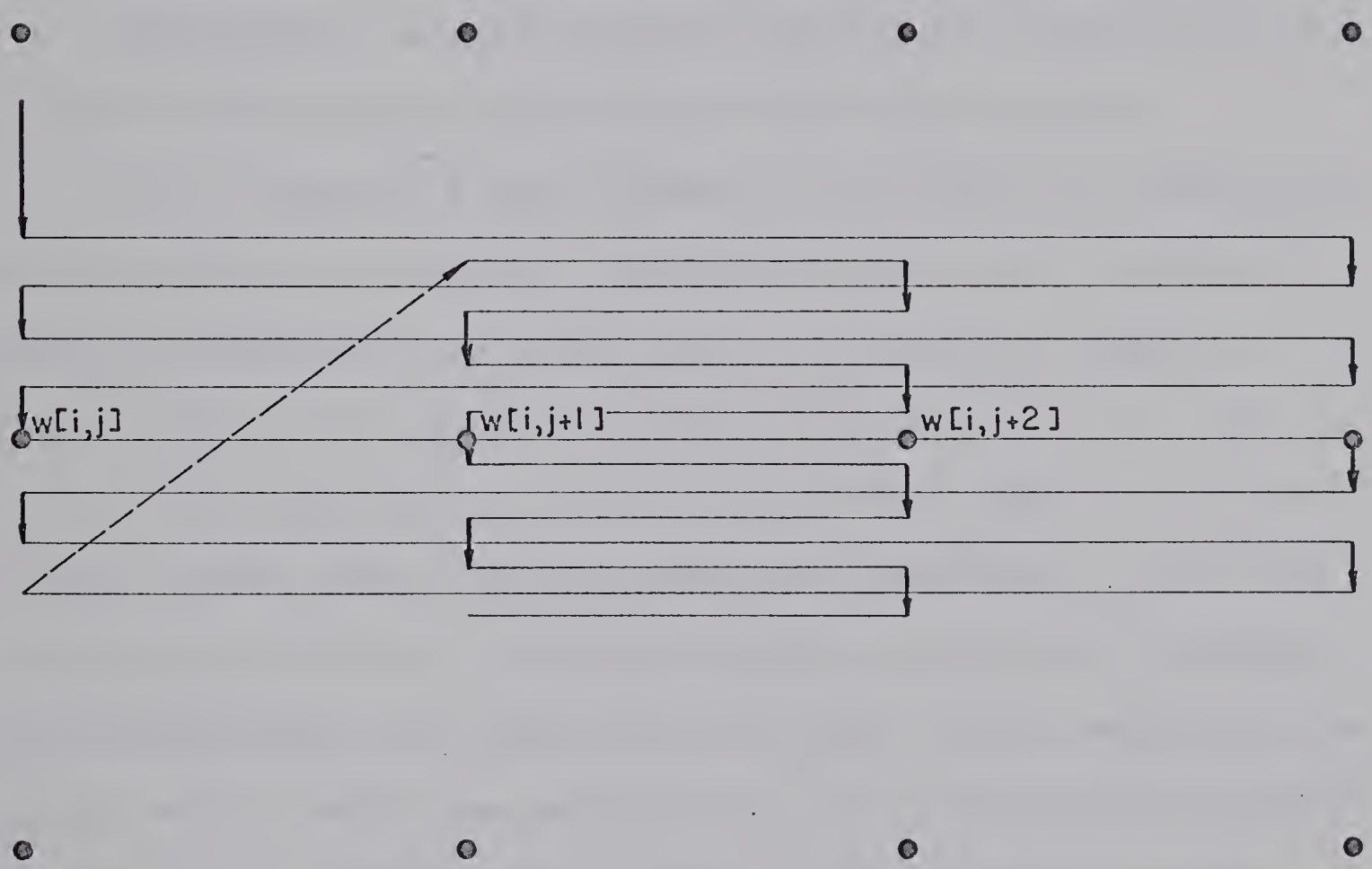


Figure 4.2.3.1 Example of beam trajectory during the display of matrix elements w[i, j], w[i, j+1] and w[i, j+2] being represented by the line densities per matrix row $N_4 = 8$, $N_5 = 16$ and $N_4 = 8$ respectively

would have to be $(40 \times 2^7) \times (40 \times 2^7)$ screen units. Such a picture cannot be displayed on a 1024 x 1024 raster. We chose the size of picture as (40 x 16) x (40 x 16). This then allowed the maximum density of lines per matrix row to equal 16 and thus five ranges of response could be distinguished. The display of up to 3 additional ranges, if requested, was achieved by refreshing some combinations of lines twice within the basic refresh cycle time. The method of combination selection is shown in Figure 4.2.3.2

Disregarding the system restrictions mentioned in Section 4.2.1 we could obviously extend such methods in the following manner.

Let us choose as a basic element of the picture the constant number of horizontal line segments which will represent the subsequence of matrix row elements w[i, j] having values in a particular range R_k. Using the notation introduced in Section 4.2.2, if $k \geq k1 + r - 1$ (r = 1, 2...m), the corresponding set of lines would be refreshed r-times during the basic refresh cycle. The lines should be distributed in such a way that spacing in the y(or j) direction would be the same over the whole area corresponding to the lowest range displayed. Such a method would be the same over the whole area corresponding to the lowest range displayed. It would also be convenient when a greater number of response ranges is to be displayed on the screen. However, there is one particular disadvantage - if a copy of the picture on the screen is required only photographic methods could be used since the resolution of a picture produced by the digital plotter would be very low.

Let us now return to the method currently implemented. To make the notation of Section 4.2.2 easier to understand consider the following simple example.

EXAMPLE:

Draw the distribution of the lines corresponding to the values w[i, j], w[i, j+1] given in the following table which will satisfy the requirements of Section 4.2.2 and the restrictions of Section 4.2.3. Maximum value of the count found on the matrix is $w[i, j]_{max} = 1000$. The variables defining the graphical representation are given as follows:

n = 10 - the number of response levels C_k

m = 8 - the number of ranges to be distinguished

k1 = 2 - the subscript of the lowest range to be displayed.

k	C_k	R_k	i	w[i, j]	w[i, j+1)
0	0				
1	100	0-99	32*	75	99
2	200	100-199	33	110	180
3	300	200-299	34	215	30
4	400	300-399	35	390	320
5	500	400-499	36	455	72
6	600	500-599	37	560	545
7	700	600-699	38	612	82
8	800	700-799	39	730	708
9	900	800-899	40	980	32
10	1000	900-999			

* To achieve correspondence of the subscripts put i = 32 in Figure 4.2.3.2.

DENSITY LEVEL: r	NO. OF VECTORS PER MATRIX ROW: N_r
0	0
1	1
2	2
3	4
4	8
5	16
6(5+3)	20
7(5+4)	24
8(5+5)	32

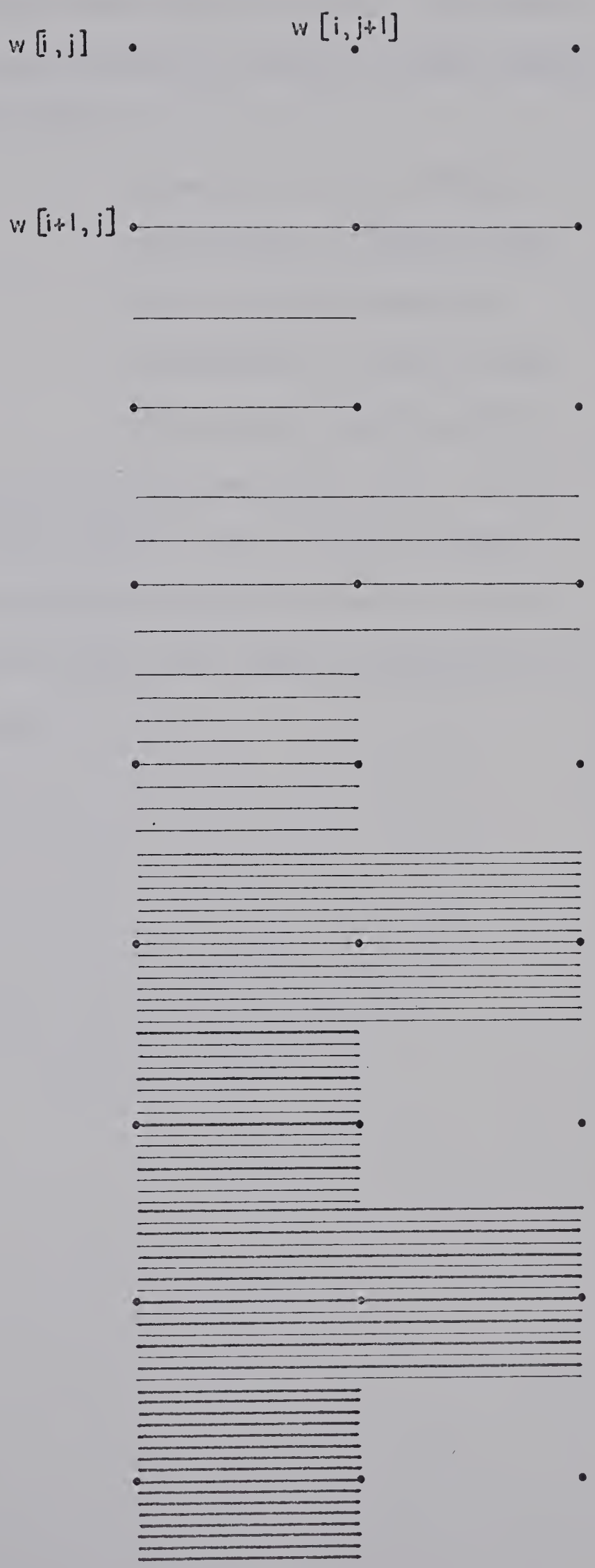


Figure 4.2.3.2 Example of horizontal line segments distribution.

To allow modification of the graphical representation of a given radioisotope distribution by changing constants n, m and k1, three parameters were defined and their values displayed as separate blocks together with the picture. These parameters are:

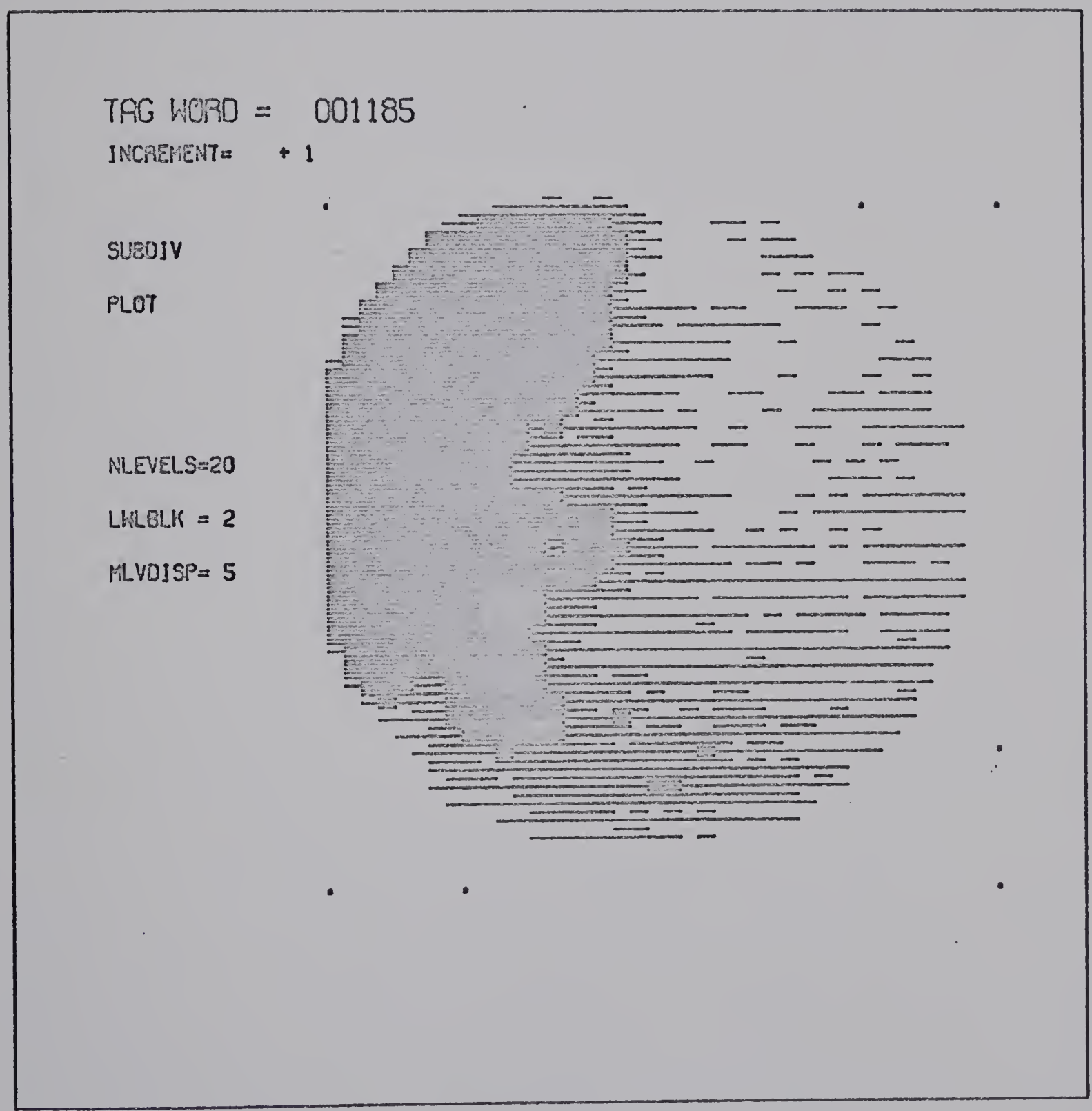
NLEVELS = n . . . . . the number of levels defined

LWLBLK = k1 - 1 . . . . . the subscript of highest range which is not yet displayed

MLVDISP = k1 + m - 1 . . . . . the subscript of highest range which is still distinguished.

The values of the parameters can be easily changed by the light pen and the alphanumeric keyboard. We shall refer to them as to the Display Parameters. Their influence on a graphical representation of a typical radiosiotope distribution, obtained during liver-pancreas experiments, is shown in the following six pictures.

Figure 4.2.3.3 Radioisotope distribution image of liver and pancreas.
Tag word = 1185, Display Parameters: 20, 2, 5.



PLOT 6 18 JULY 1970

Figure 4.2.3.4 Radioisotope distribution image of liver and pancreas. Tag word = 1185, Display Parameters: 20,4, 7.

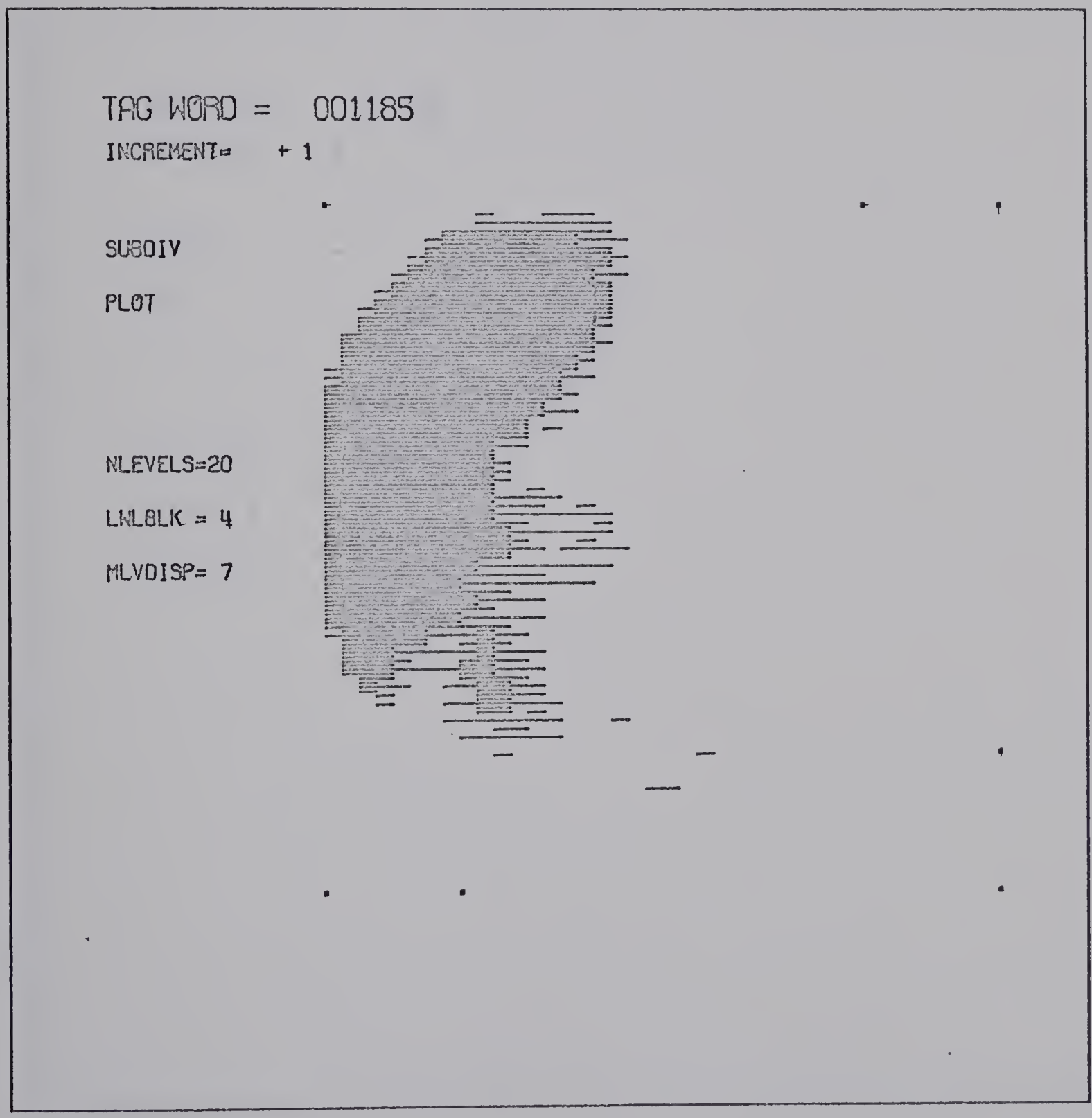
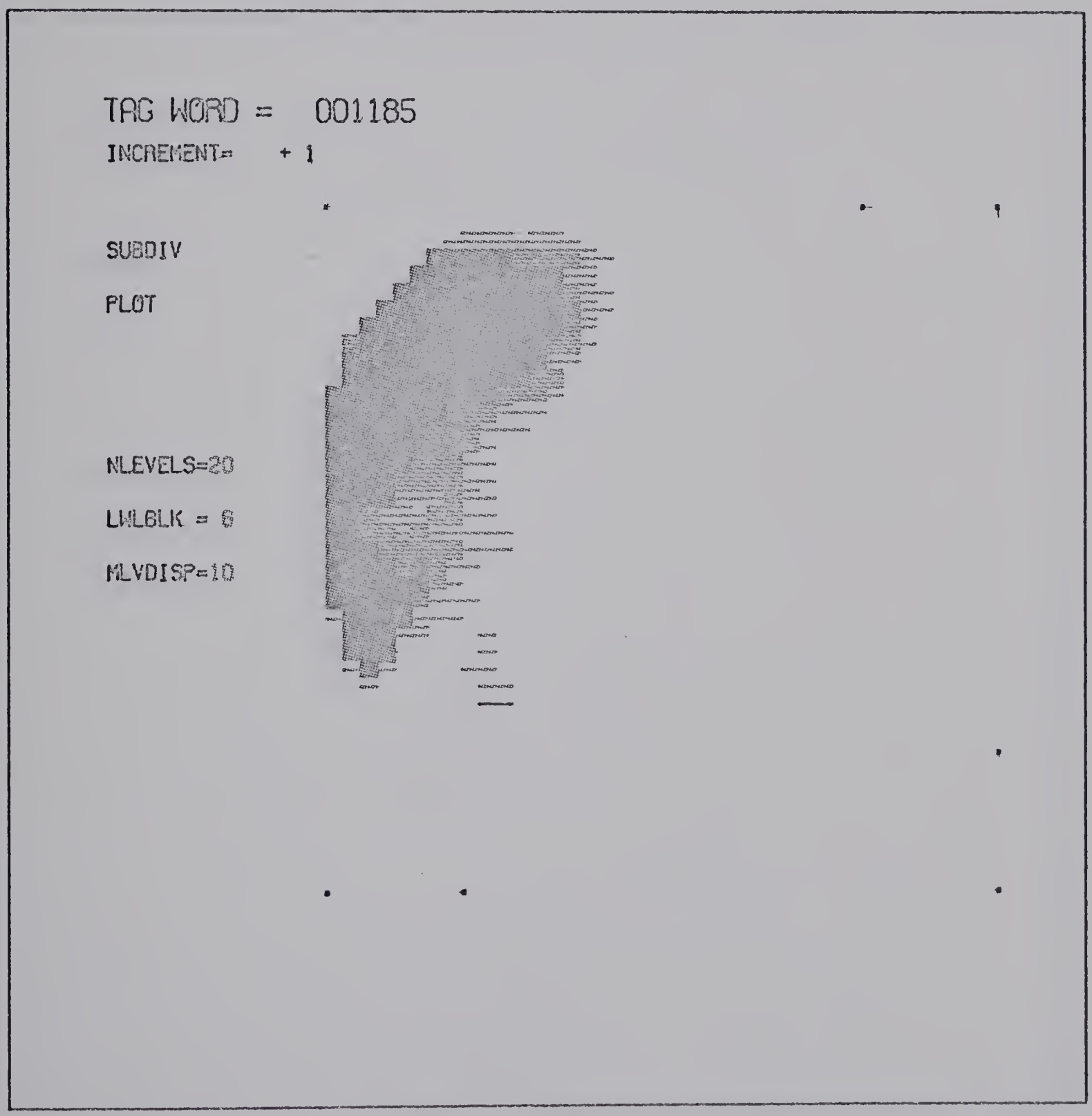


Figure 4.2.3.5 Radioisotope distribution image of liver and pancreas. Tag word = 1185, Display Parameters: 20, 6, 10.



PLOT 3 18 JULY 1970

Figure 4.2.3.6 Radioisotope distribution image of liver and pancreas.
Tag word = 1185, Display Parameters: 20, 6, 9.

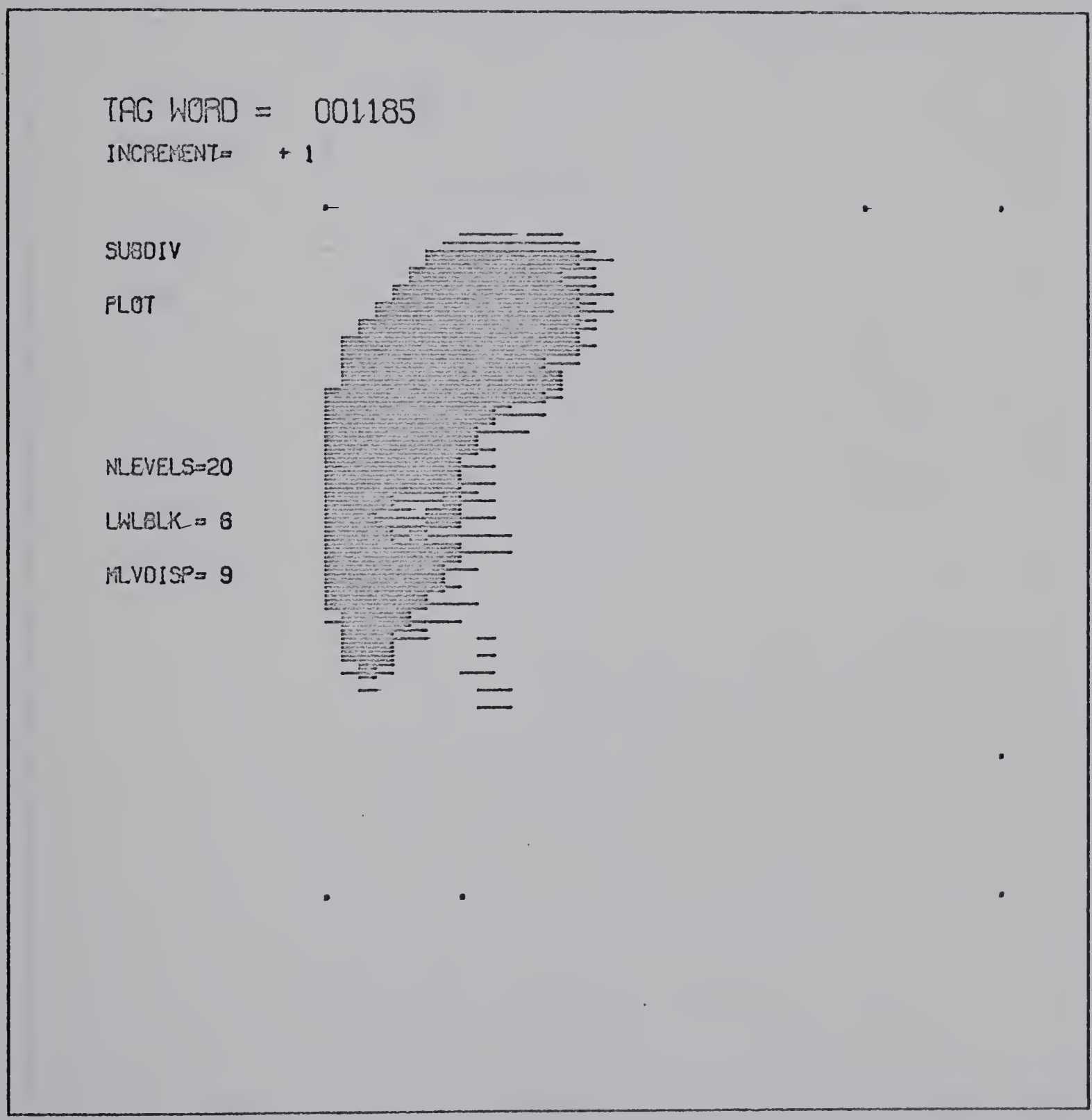


Figure 4.2.3.7 Radioisotope distribution image of liver and pancreas. Tag word = 1185, Display Parameters: 20, 8, 12.

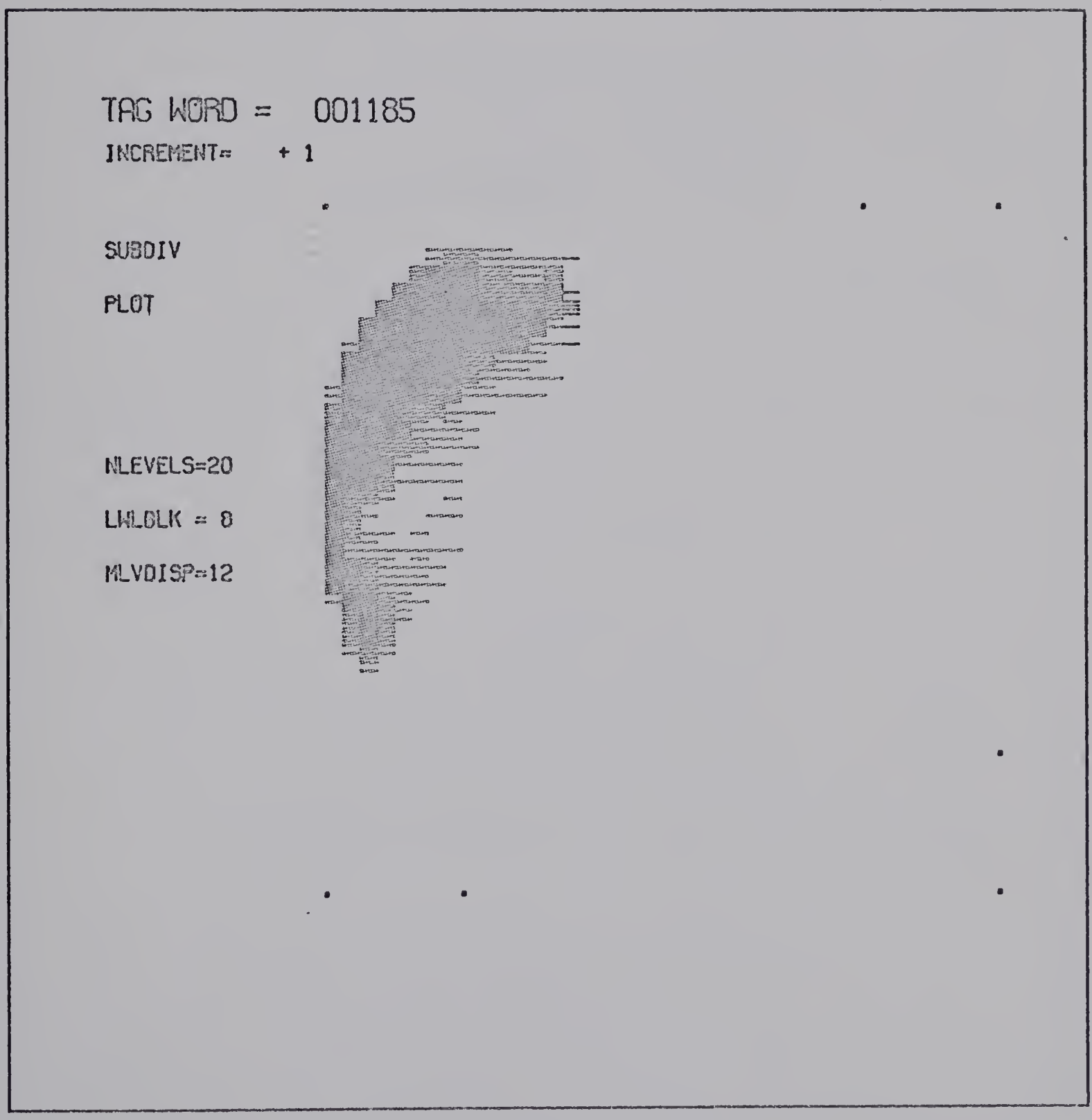


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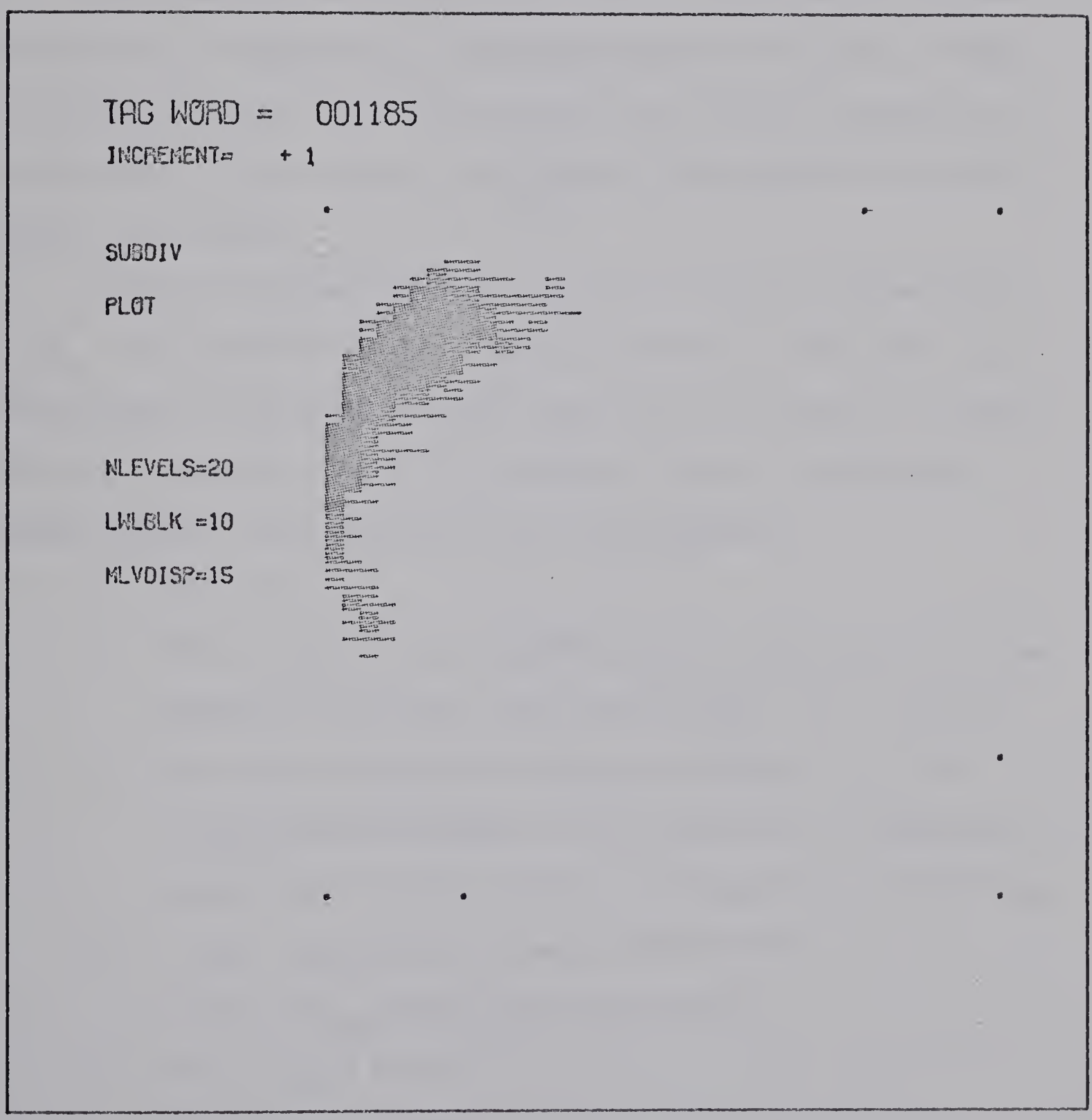
Figure 4.2.3.8 Radioisotope distribution image of liver and pancreas.
Tag word = 1185, Display Parameters: 20, 10, 15.



4.3 Boundary and Subdivision Specification

Suppose now that the graphical representation of the radioisotope distribution allows visual identification of an area of interest. The next step in the evaluation process consists of specification of a boundary and/or subdivision by the light pen.

With the light pen in the track mode the GRID supervisor allows the boundary to be specified by the defined sequence of vectors. Using the function keyboard the terminal operator can add the coordinates of the end points of each vector to the message being assembled for transmission to the 360/67.

Figure 4.3.1 shows how such a sequence of points, denoted by b_1, $b_2 \ldots b_k \ldots$ and specified by their (x, y) coordinates in the screen coordinate system, is evaluated to obtain the sequence of nodes [i, j] which defines the boundary in the [i, j] coordinate system. The algorithm (routine BNDIND) can be described in the following way:

1 Put $k = 1$.

2 Find the constants C_k, q_k which analytically specify the line obtained by extension of the vector $\overline{b_{k+1} b_k}$, ($C_k = tg\ (\beta_k)$).

3 Using the transformation formulae between the (x, y) and [i, j] coordinate systems and with appropriate rounding procedure find and store the node corresponding to the point b_k.

4 If $|C_k| > C_{max}$ (slope infinity) then GO TO 2,
if $|C_k| < C_{min}$ (slope zero) then GO TO 9.

5 If $x_k - x_{k+1} < 0$ then $j = j - 1$,
if $x_k - x_{k+1} > 0$ then $j = j + 1$.

6 If j corresponds to b_{k+1} then GO TO 8.

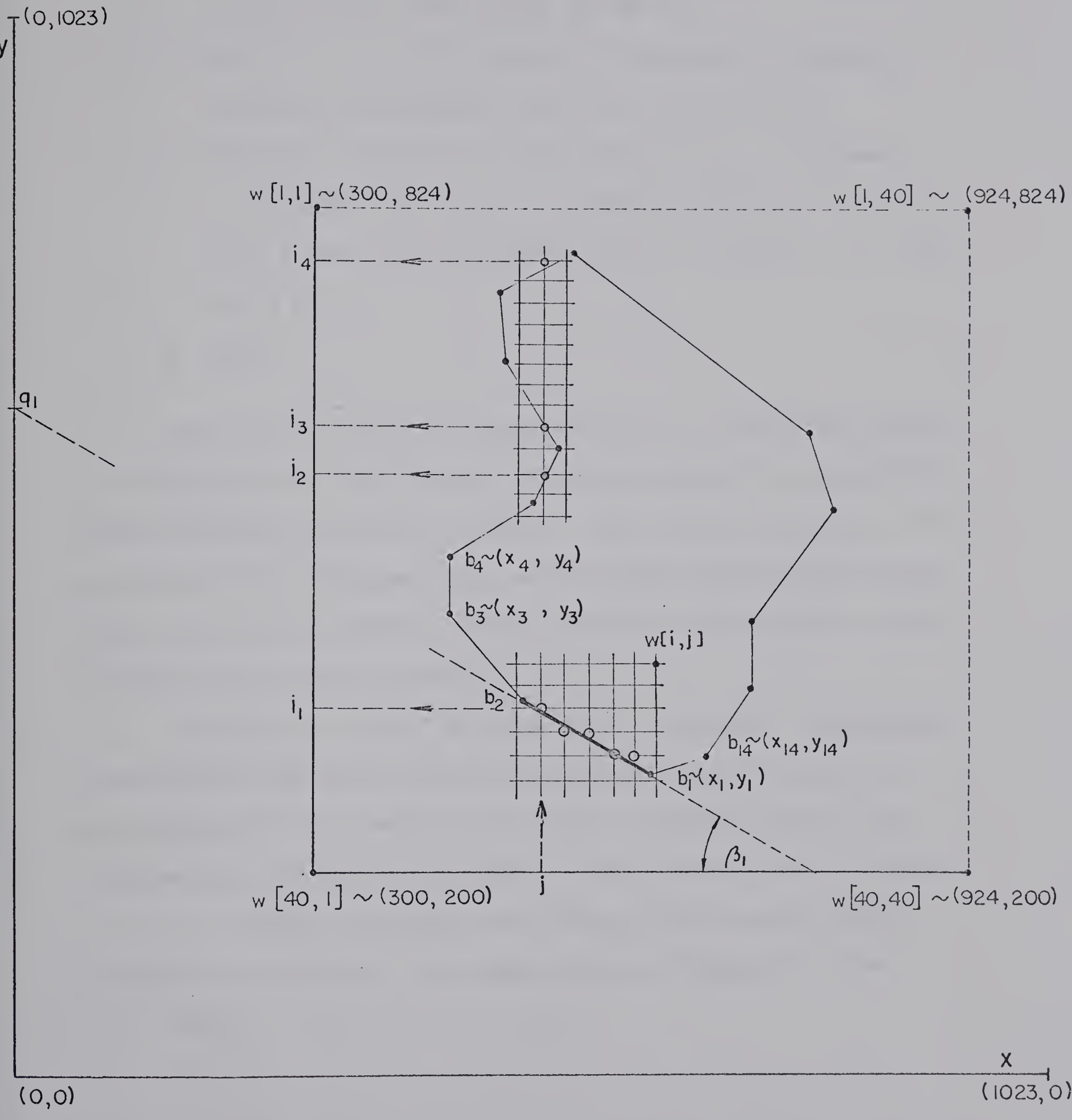


Figure 4.3.1 Boundary transformation scheme

7 For a new index j find and store the node [i, j] located closest to the vector $\overline{b_{k+1} b_k}$ and GO TO 5.

8 Put k = k + 1. If k is equal to the number of points b_k specifying the boundary then GO TO 10 else GO TO 2.

9 Find the coordinate j* corresponding to b_{k+1}. Increment (repeatedly) j by +1 or -1 to approach the value j* and for each j store the corresponding node [i, j] until j = j*, then GO TO 8.

10 END.

The specification of a boundary in the [i, j] coordinate system is used for each matrix of a series or for each matrix from a specified range of interest by the routine SUBINT. This routine, according to the parameters in the calling sequence, performs fixed point integration on ||w[i, j]|| over the elements inside or outside of the boundary, or substitutes zeros for these elements.

To obtain an easy way of handling these operations the boundary is specified by two arrays with dimensions NOI (40) and IJ (10, 40). Each element NOI (j) is equal to the number of boundary nodes [i, j] corresponding to the particular index j. The elements IJ (m, j), where m = 1, 2,... NOI(j), are equal to the values of the boundary node's i-indexes for particular j. For index j shown on Figure 4.3.1 then

NOI(j) = 4

IJ(1, j) = i_1

IJ(2, j) = i_2

IJ(3, j) = i_3

IJ(4, j) = i_4.

If subdivision of the matrix into a number of compartments is required, it will probably be different for each particular experiment. To be able to provide this function in the data reduction process, the user must supply corresponding subroutines; their implementation is, however, facilitated by routines already incorporated in DRISP. For example, in studies of radioisotope distribution dynamics, the display of a separate graph for each compartment could be required. The routine GRAPH enables easy specification of graph origin, its size and the specification of identification numbers for blocks to be used for the graph display. (The display of messages associated with the graph can also be inhibited.) This enables the display of a number of graphs on the screen at the same time or organization of graphical output of the results into the display pages in the block file.

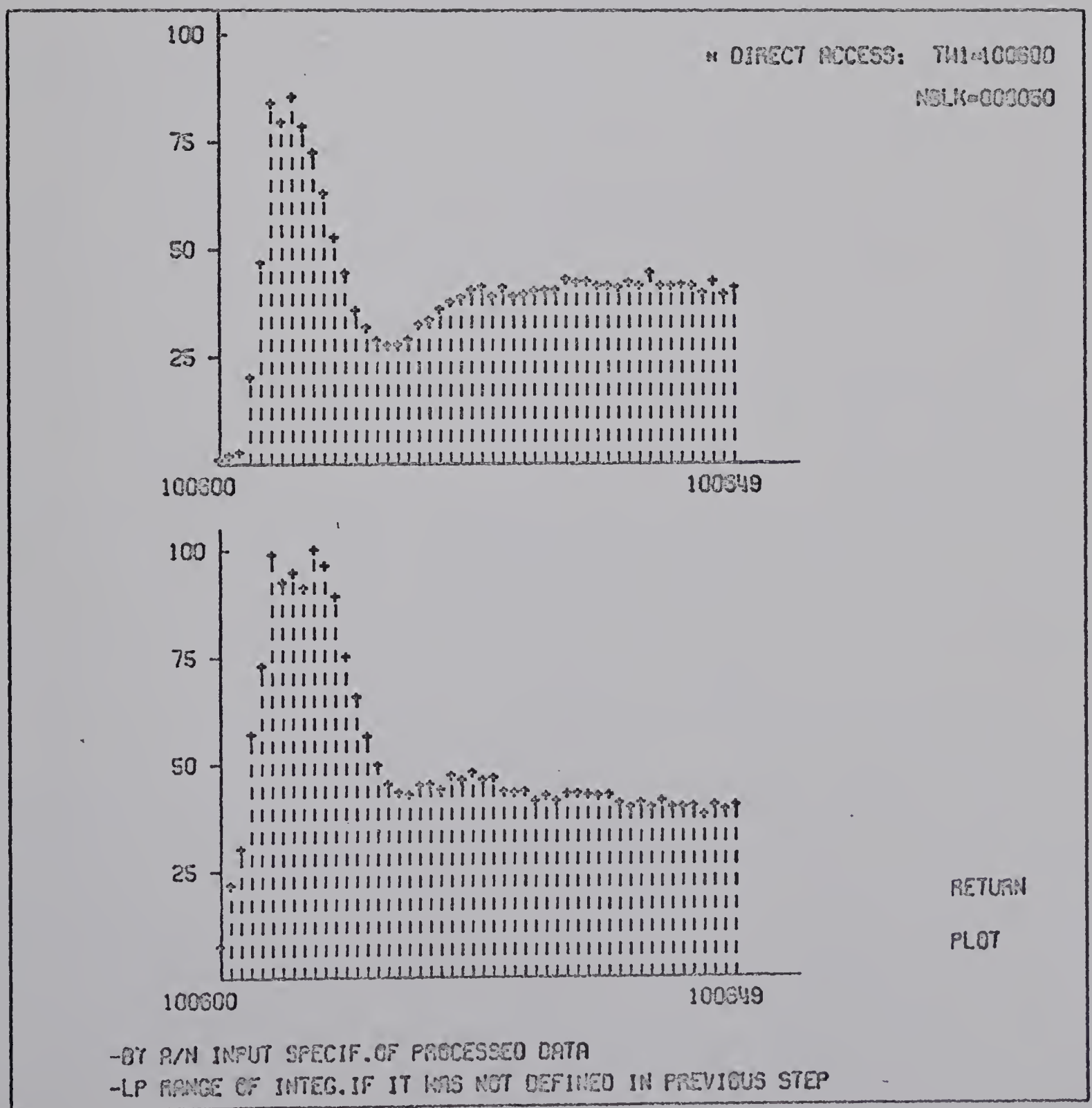
An example of simple subdivision of the matrix into six compartments is shown in Figure 4.3.2 The subdivision was specified simply by drawing a vertical line dividing the left and right lung fields with a length equal to the vertical dimension of the lung images on the screen. The coordinates of the end points of the line provide, after transmission into the 360/67, the information necessary for subdivision of the matrix into six rectangular compartments as is shown in Figure 4.3.2.

The location of graphs on the screen representing the results of an evaluation of two compartments of the specified series of matrices is shown at Figure 4.3.3 (the display page).

To avoid writing the supplementary subroutines it is possible, however, to specify the boundary of the compartment using the boundary definition technique outlined above, carry out compartment evaluation, and then proceed in the same way with subsequent compartments.

Figure 4.3.2 Example of subdivision of matrix into six rectangular compartments

Figure 4.3.3 Location of the graphs on the screen



Such a technique would probably be useful in cases where more sophisticated matrix subdivision is required. The transfer of some matrix area (for all matrices from the range of interest) into the "working space" on discs could well be used. The specification of lung margins described in Chapter V is an example of such a technique.

4.4 Specification of the Command Language

In previous sections we have discussed the methods which allow utilization of functions satisfying the requirements of Section 4.1. Because of the interactive nature of these methods we have to define appropriate actions for the operator, or in other words, how to control the execution of the program in the 360/67 by means of the light pen and function or alphanumeric keyboards. To be able to use the functions an exact definition of allowed commands and their sequence has to be stated. In the following command language specification, besides the basic components of commands, two categories of commands are defined; a command block and a command string.

Each command block corresponds to the entry in the Decision Table. By command block the operator requests basic functions of the data reduction process. These basic functions can be executed directly by the command block (e.g. transfer of data from the tape on disc) or a particular command string has to be used (e.g. if functions related to the Boundary Options Table are to be carried out). In such a case the input of the command block from the terminal will result in the display of a new table or graph(s) which enable the command string specification. The command string specification then begins with the particular command block.

By command string the subfunctions which facilitate the data reduction functions are carried out (e.g. the change of Display Parameters). In their syntax definitions, however, the command blocks are often used to specify a preceeding sequence of command components.

In the following syntax specification symbols input, by picking with the light pen, are delimited with quotes, e.g. 'PLOT'. Other

input sources are explained by notes, e.g.:

<DIGIT>::= 0|1|2|....|9 (digits input from alphanumeric keyboard)

BASIC COMPONENTS OF COMMANDS

Syntax:

<COMPONENT>::=<DIGIT>|<CHARACTER>|<TAG WORD>|
<NUMBER OF BLOCKS>|<LPGRAPH>|
<SPECIFICATION>|<LINE>|<SEND>|
<INCREMENT>

<DIGIT>::= 0|1|....|9 (digits input from aphpanumeric keyboard)

<CHARACTER>::=<DIGIT>|A|B|C|...(i.e. any character from GRID character set, input from alphanumeric keyboard)

$<TAG\ WORD>::=\{<DIGIT>\}^{6}$

$<NUMBER\ OF\ BLOCKS>::=\{<DIGIT>\}^{6}$

<LPGRAPH>- TWO CONSECUTIVE LIGHT PEN HITS OF THE GRAPH ORDINATES

$<SPECIFICATION>::=\{<CHARACTER>\}_{1}^{40}$

<LINE>- A VECTOR INPUT BY USE OF THE LIGHT PEN AND FUNCTION KEYBOARD

<BLANK>::= BLANK CHARACTER (input from alphanumeric keyboard)

<SIGN>::=<BLANK>+ |<BLANK>-

<PARAMETER VALUE>::= <BLANK><DIGIT>|10|11|....|31|32

<INCREMENT VALUE>::= <SIGN><PARAMETER VALUE>

<SEND>::= # (i.e. end of message; input by pressing SEND key)

<INCREMENT>::= <SEND>

<SKIP>::= <SEND>

COMMAND BLOCKS

Syntax:

<COMMAND BLOCK>::=<DIRECT ACCESS FILE>[<MATRIX DISPLAY>
<BOUNDARY SUBTRACTION>|<SERIES INTEGRATION>|
<SUBDIVISION INTEGRATION>

Syntax:

<DIRECT ACCESS FILE>::= '*DIRECT ACCESS: TW1 = NBLK ='
<TAG WORD>{<CHARACTER>}^{4} <NUMBER OF BLOCKS>
<SEND>

Semantics:

Transmit data from the tape into the direct access file. The Decision Table is again being displayed.

Syntax:

<MATRIX DISPLAY>::= 'A*MATR. DISPLAY' <SEND>
<TAG WORD><SEND>

Semantics:

Specify the tag word and display the corresponding matrix. The following functions can be carried out:

- boundary or subdivision specification,
- dump of the display file for plot,
- change of display parameters or increment,
- display of new matrix specified by A/N keyboard or automatically according to present value of increment,
- display of Decision Table.

Syntax:

<BOUNDARY SUBTRACTION>::= 'B* BOUNDARY SUBTR.'<TAG WORD>{<CHARACTER>}^{4}
<TAG WORD><SEND>

Semantics:

Display the Boundary Options Table and specify tag word range. The following functions can be carried out:

- subtraction from each matrix of the series the elements w[i, j] located outside or inside the boundary and the storage of resulting matrices on the disc starting at the record of the specified associated variable,
- integration of each matrix of the series over elements outside or inside the boundary and display of the normalized graph of the integrals against corresponding tag words,
- display of Decision Table.

Syntax:

<SERIES INTEGRATION>::='C* SER. INTEGR.' <TAG WORD>{<CHARACTER>}^{4}
<TAG WORD><SEND>

Semantics:

Integrate each matrix of the series and display normalized graph of the integrals against corresponding tag words. The following functions can be carried out:

- input of the graph specification by means of the alphanumeric keyboard,
- specification of the range of interest in the series,
- dump of the display file for plot,
- display of Decision Table.

Syntax:

<SUBDIVISION INTEGRATION>::= 'D* SUBDIV. INTEGR.' <TAG WORD>

{<CHARACTER>}^{4}<TAG WORD><SEND>

Semantics:

Integrate separately each compartment of the matrix subdivision for all matrices of the series and display the graph for each compartment. The following can be carried out:

- input of the graphs specification for each display page,
- dump of the display file for plot,
- specification of the range of interest in the series,
- display of new display page,
- display of Decision Table.

COMMAND STRINGS

Syntax:

<COMMAND STRING>::=<BOUNDARY>|<BOUNDARY SPECIFICATION>|<SUBDIVISION>|<SUBDIVISION SPECIFICATION>|<PARAMETER>|<PARAMETERS>|<INTEGRATE INSIDE>|<INTEGRATE OUTSIDE>|<ZERO INSIDE>|<ZERO OUTSIDE>|<GRAPHS>|<RANGE>|<RETURN>|<END>

Syntax:

<BOUNDARY>::=<MATRIX DISPLAY><BOUNDARY SPECIFICATION><SEND>|<MATRIX DISPLAY><BOUNDARY SPECIFICATION>'PLOT'<SEND>|<PARAMETERS><INCREMENT><BOUNDARY SPECIFICATION><SEND>|<PARAMETERS><INCREMENT><BOUNDARY SPECIFICATION>'PLOT' <SEND>

Semantics:

Specify the area of interest on the graphical representation of the matrix.

Syntax:

<BOUNDARY SPECIFICATION>::=<LINE>|<BOUNDARY SPECIFICATION><LINE>

Semantics:

Use the light pen and function keyboard to specify boundary.

Syntax:

<SUBDIVISION>::=<MATRIX DISPLAY>'SUBDIV'<SUBDIVISION SPECIFICATION><SEND>|
<MATRIX DISPLAY>'SUBDIV'<SUBDIVISION SPECIFICATION>'PLOT'<SEND>|
<PARAMETERS><INCREMENT>'SUBDIV'<SUBDIVISION SPECIFICATION><SEND>|
<PARAMETERS><INCREMENT>'SUBDIV'<SUBDIVISION SPECIFICATION>'PLOT'<SEND>

Semantics:

Specify the compartments of the subdivision of the matrix.

Syntax:

<SUBDIVISION SPECIFICATION>::=<LINE>|<SUBDIVISION SPECIFICATION><LINE>

Semantics:

Use light pen and function keyboard to specify subdivision.

Syntax:

<PARAMETER>::='NLEVELS = '<PARAMETER VALUE><SEND>|'LWLBLK = '<PARAMETER
VALUE><SEND>|'MLVDISP='<PARAMETER VALUE><SEND>|'INCREMENT= '<SIGN>
<PARAMETER VALUE><SEND>

<PARAMETERS>::=<PARAMETER>|<PARAMETERS><PARAMETER>

Semantics:

Change any of the Display Parameters or value of increment.

Syntax:

<INTEGRATE INSIDE>::=<BOUNDARY SUBTRACTION>'*INTEGR. IN'<SEND>

Semantics:

For each matrix of the series integrate w[i, j] located inside the boundary and display the normalized graph.

Syntax:

<INTEGRATE OUTSIDE>::=<BOUNDARY SUBTRACTION>'*INTEGR. OUT' <SEND>

Semantics:

For each matrix of the series integrate elements w[i, j] located outside the boundary and display the normalized graph.

Syntax:

<ZERO INSIDE>::=<BOUNDARY SUBTRACTION>'*STORE AREA:'{<DIGIT>}^{6}<SEND>
'*ZERO IN' <SEND>|<BOUNDARY SUBTRACTION><RETURN>

Semantics:

Subtract from each matrix of the series the elements w[i, j] located inside the boundary and store resulting matrices on the disc.

Syntax:

<ZERO OUTSIDE>::=<BOUNDARY SUBTRACTION>'*STORE AREA:'{<DIGIT>}^{6}<SEND>
'*ZERO OUT' <SEND>|<BOUNDARY SUBTRACTION><RETURN>

Semantics:

Subtract from each matrix of the series the elements w[i, j] located outside the boundary and store resulting matrices on the disc.

Syntax:

<GRAPHS>::=<SERIES INTEGRATION>|<SUBDIVISION INTEGRATION>|<INTEGRATE INSIDE>|<INTEGRATE OUTSIDE>

Semantics:

Display graph/graphs using the command block

<SERIES INTEGRATION> or <SUBDIVISION INTEGRATION> or command string

<INTEGRATE INSIDE> or <INTEGRATE OUTSIDE>.

Syntax:

<RANGE>::=<GRAPHS><LPGRAPH><SEND>|<GRAPHS><SPECIFICATION><LPGRAPH><SEND>|

<GRAPHS><SPECIFICATION><SEND>|<GRAPHS><SEND>

Semantics:

Display the graph/graphs and define the range of interest by the light pen.

Syntax:

<RETURN>::='RETURN'<SEND>

Semantics:

Display the Decision Table.

Syntax:

<END>::='END' <SEND>

Semantics:

Finish the execution of subroutine GRAPHIC and pass control to MCR.

(That is, terminate the session at the display terminal.)

CHAPTER V

PULMONARY PERFUSION DATA MANIPULATION

Having defined the command language we shall demonstrate the use of DRISP for manipulation of data obtained in measurements of regional pulmonary perfusion in humans. The experimental methods were briefly outlined in Chapter II.

At the beginning of a graphics terminal session the Decision Table is displayed (Figure 5.1.A) and the operator creates the direct access file by specifying the tag word to be found on the tape and the number of consecutive blocks (matrices) to be transferred to disc. These actions correspond to the command block

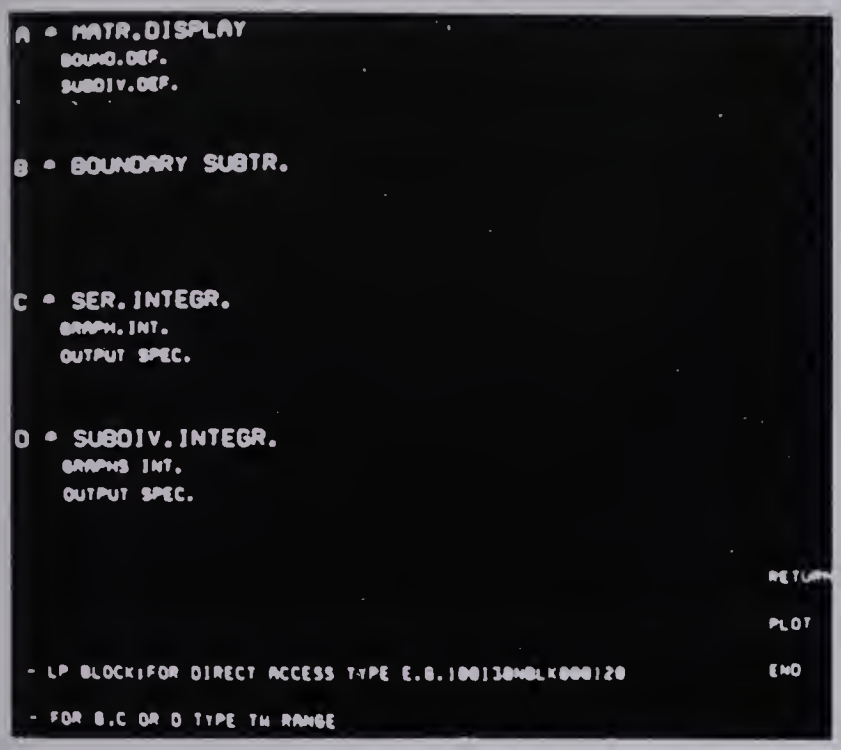
<DIRECT ACCESS FILE>

or specifically, in correspondence with Figure 5.1 and 5.2, to the sequence

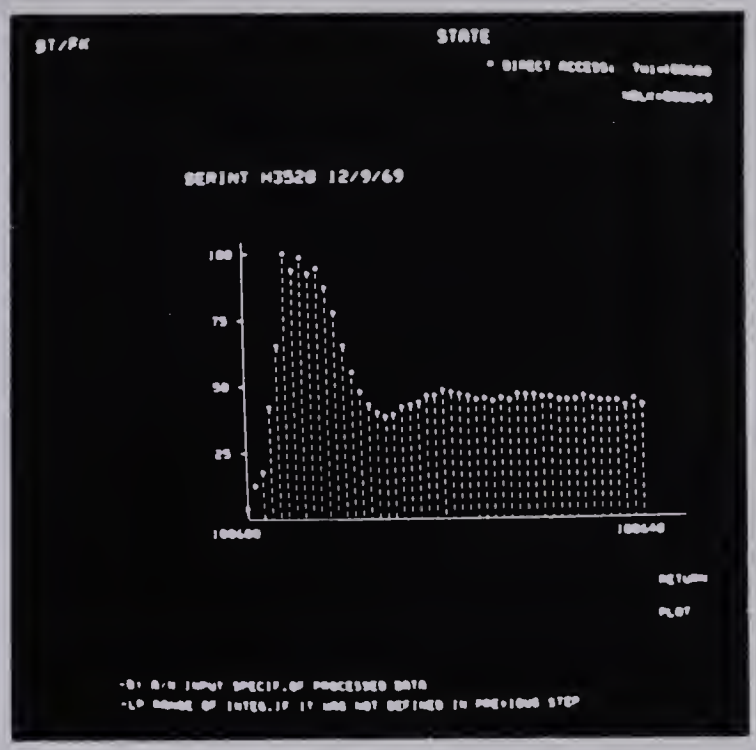
'* DIRECT ACCESS: TW1 = NBLK = '100600 NBLK 000049 <SEND>.

Data are stored on disc as a sequential set and during the data transfer the list of tag words with corresponding associated variables is created in the 360/67 core (routine TWLIST). The list enables later addressing and transfer of the matrices to be evaluated into the 360/67 core. The first fifty blocks of the file are reserved as working space and the tag words of these blocks in the list are equal to the corresponding associated variables (i.e. first tag word on the list is 000001). The block diagram of a data structure is shown in Figure A.3 of the Appendix.

The operator now has to specify the series from the direct access file which is to be evaluated. To obtain a first estimate of the range of interest in the series the graph of the integrals over the matrices



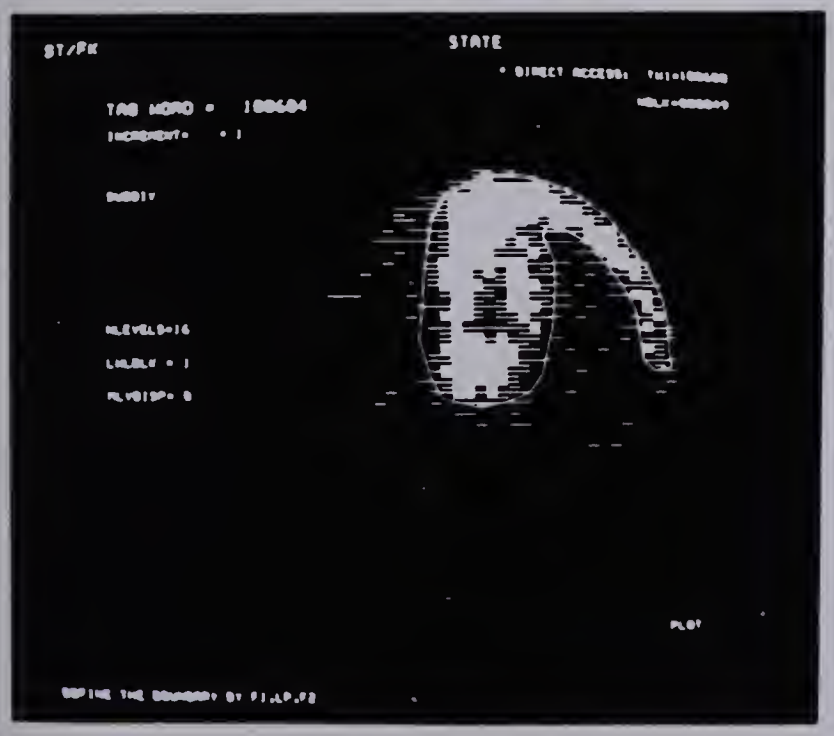
A



B

C

D



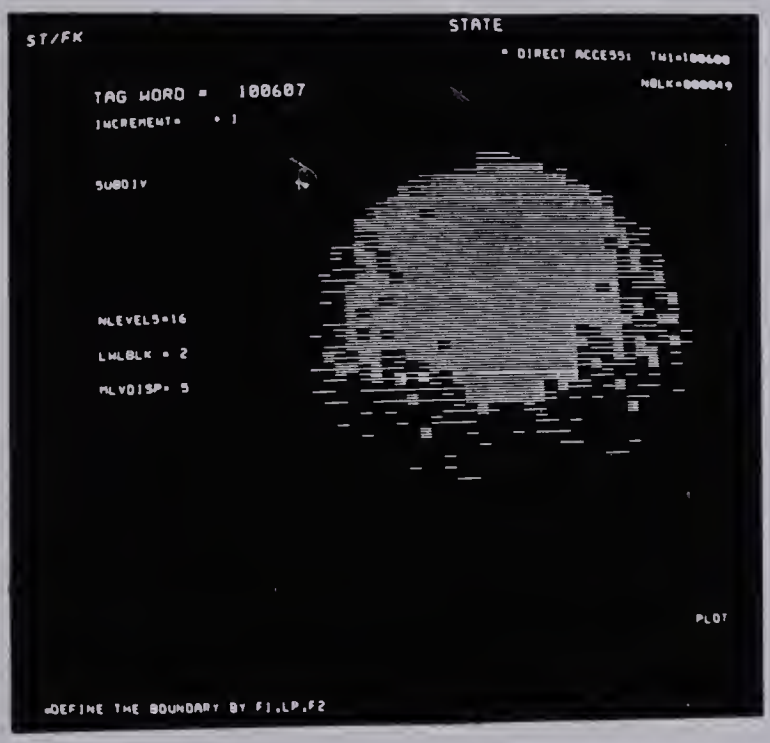
E

F

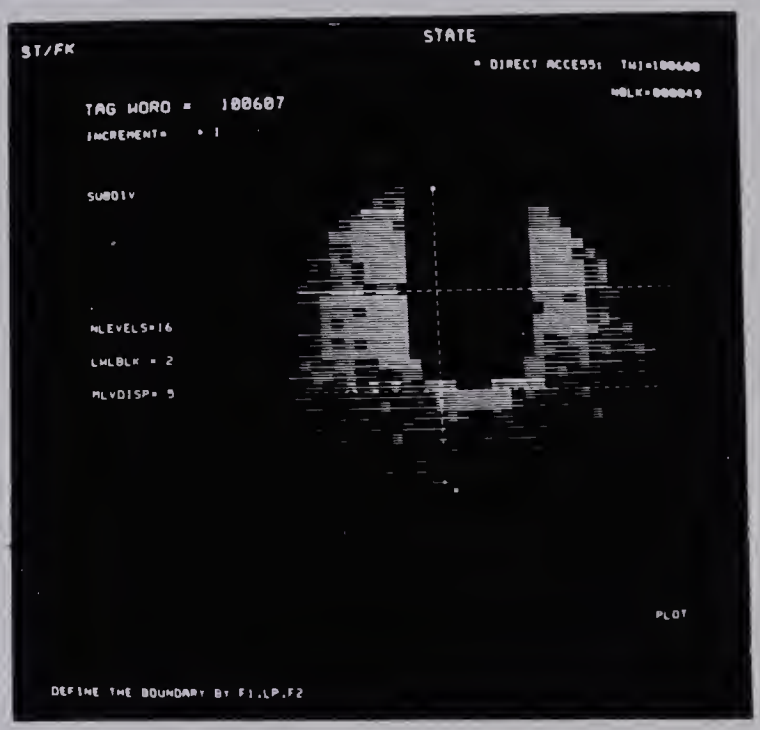
FIGURE 5.1

A

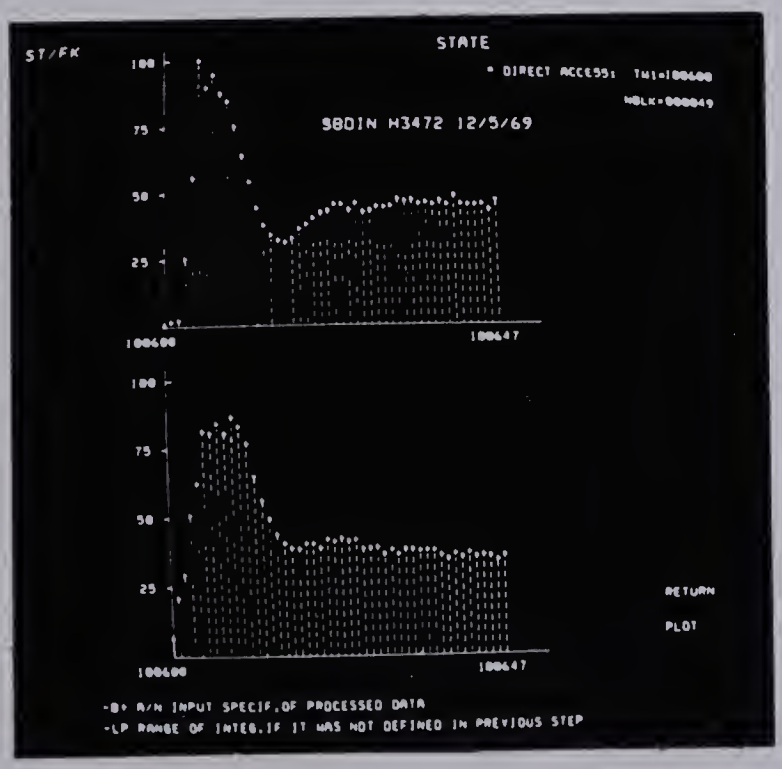
B



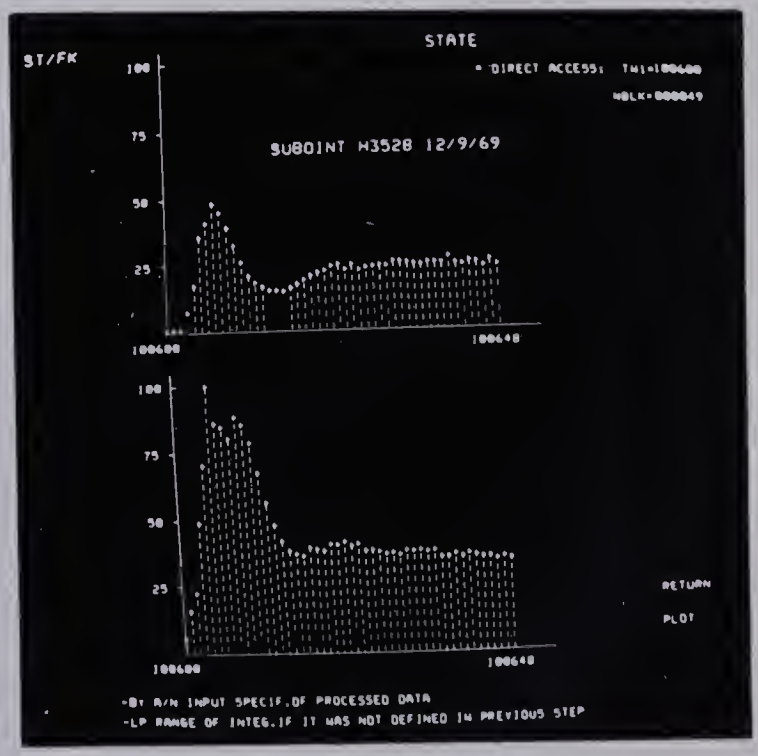
C



D



E



F

FIGURE 5.2

against corresponding tag words is displayed (Figure 5.1.B) by the command block

<SERIES INTEGRATION>

or specifically by the sequence:

'C* SER. INTEGR.' 100600 <BLANK> TO <BLANK> 100648 <SEND>.

From the graph it can be seen that the area of the heart can be defined on a matrix in the range 100602 - 100605 and that the "recirculation" of radioisotope starts in the second third of the series (corresponding matrices have to be excluded from evaluation). The specification of the graph and the location of the peak (the range of interest) correspond to the command string

<RANGE>

or specifically, in correspondence with Figure 5.1.B, to the sequence

SERINT <BLANK> H3528 <BLANK> 12|9|69 <LPGRAPH><SEND>.

The alphanumeric keyboard was used to input the graph specification and this action by the operator also results in the output of the graph copy on the line printer together with the average response (i.e. average integral over the matrices from the range of interest). After the input of the command string <RANGE> the Decision Table is again displayed.

In the next step the boundary of the heart should be specified. To display the radioisotope inflow (Figure 5.1.C), the operator inputs the command block

<MATRIX DISPLAY>

or specifically the sequence

'A * MATR. DISPLAY' <SEND> 100603 <SEND>.

The initial value of the increment is +1 and if there is no need to change the Display Parameters the operator can now display the following matrix

of the series by the basic command component sequence

<SKIP><INCREMENT>

The command component <SKIP> corresponds to the boundary or subdivision specification. The command string <BOUNDARY SPECIFICATION> or <SUBDIVISION SPECIFICATION> could have been input after the matrix 100603 was displayed. This was indicated by a message on the screen. The change of Display Parameter MLVDISP, the display of the following matrix and the boundary specification as it is shown on Figure 5.1.E, are achieved by input of the sequence

<SKIP><PARAMETERS><INCREMENT><BOUNDARY SPECIFICATION><SEND>

or specifically by the sequence

<SKIP>'MLVDISP = '<BLANK> 5 <SEND><INCREMENT><BOUNDARY SPECIFICATION> <SEND>.

The change of two Display Parameters and the display of matrix 100605 (Figure 5.2.A) are achieved by input of the sequence

<PARAMETERS><INCREMENT>

or specifically by the sequence

'LWLBLK = '<BLANK> 2 <SEND>'MLVDISP = '<BLANK> 6 <SEND><INCREMENT>.

On Figures 5.2.B and C the inflow of radioisotope into the lung fields is apparent and the matrix 100606 is the first matrix to be used for the evaluation of pulmonary perfusion (beginning of the range of interest).

The operator displays the Decision Table by the command string <RETURN> and, to be able to carry out the subtraction of the elements inside the boundary of the heart from the matrices of the series, he displays the Boundary Options Table by the command block

<BOUNDARY SUBTRACTION>

or specifically by the sequence

'B * BOUNDARY SUBTR.' 100606 <BLANK> TO <BLANK> 100616 <SEND>.

The functions which can be selected from this table are listed on page 57 where the semantics of the command string <BOUNDARY SUBTRACTION> was defined.

To be able to specify the subdivision of the lungs and the margins of lung fields the operator selects the subtraction, with the consecutive storage of resulting matrices into the working space, by the sequence

' * STORE AREA: '000001 <SEND>'* ZERO IN' <SEND>.

(This sequence follows the command block <BOUNDARY SUBTRACTION> in the syntax definition of the command string <ZERO INSIDE>.) The Decision Table is still being displayed and the operator can now display the matrices after subtraction and specify the subdivision of the matrix, as it is shown on Figure 5.2.D, by the command string <SUBDIVISION> (the tag word 000002 has to be input from the alphanumeric keyboard), or the margin of the lung field, as it is shown on Figure 5.3, by the command string <BOUNDARY>. Figures 5.2.E and 5.2.F show results after the integration over the four compartments of the subdivision. First display page (Figure 5.2.E) is displayed on the screen by the command block <SUBDIVISION INTEGRATION>.

The area of right lung field on the matrices from the range of interest corresponding to the margin as it was specified on Figure 5.3 can be stored in the working space by the command string <ZERO OUTSIDE>. The display of the matrix 100607 from the working space after the subtraction of the area outside the right lung field was carried out is shown in Figure 5.4.

For the evaluation of changes in regional pulmonary perfusion a number of numerical procedures are included; their description, however, is beyond the scope of this thesis. The corresponding subroutines can be included in DRISP to evaluate the matrices created during the data reduction process in the working space or to evaluate the experimental data directly using graphics derived information relating to the area of interest on a matrix or to the range of interest in the matrix series.

Figure 5.3 Display of the radioisotope distribution in the lung fields with the boundary specified for the right lung.

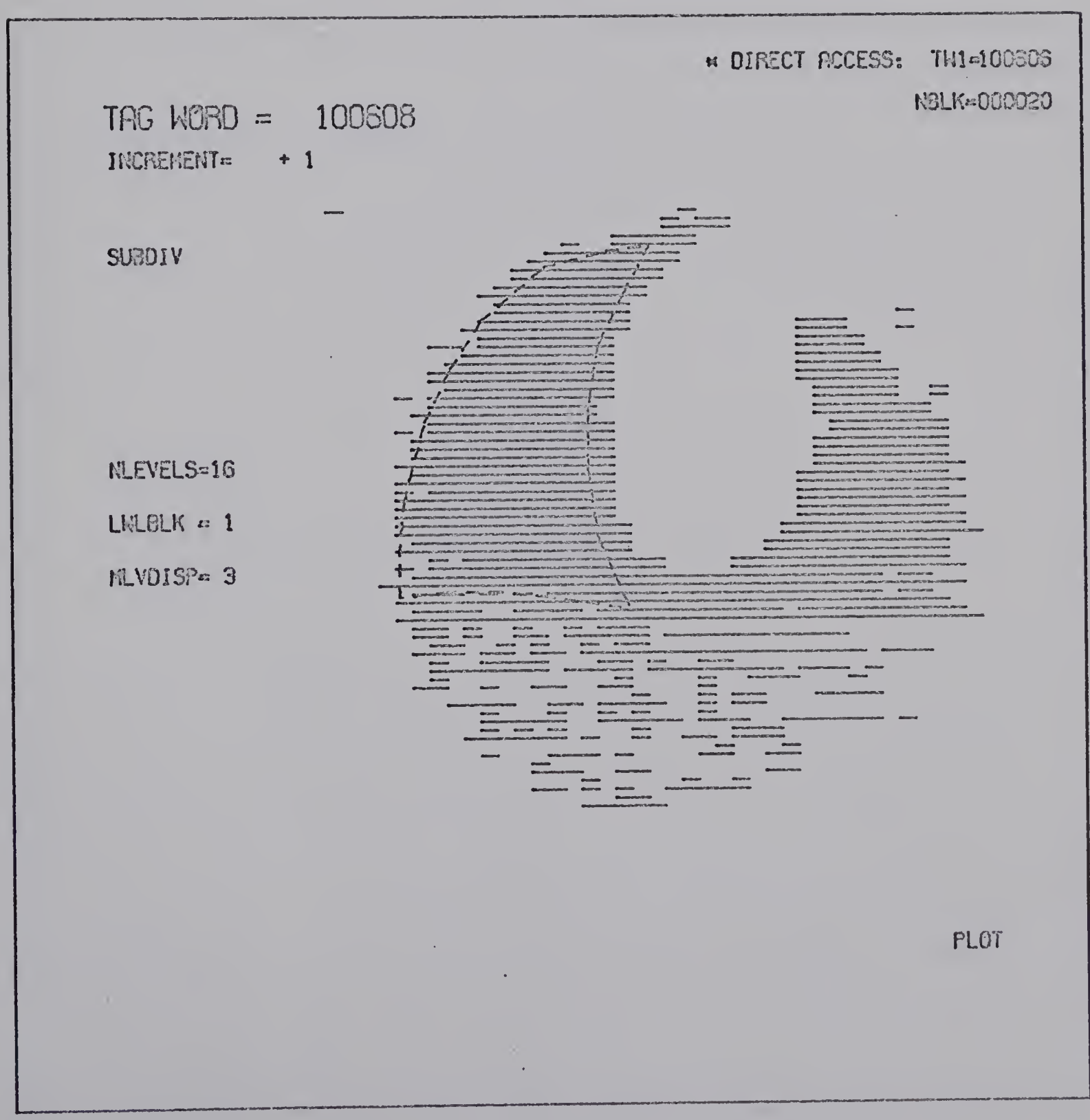
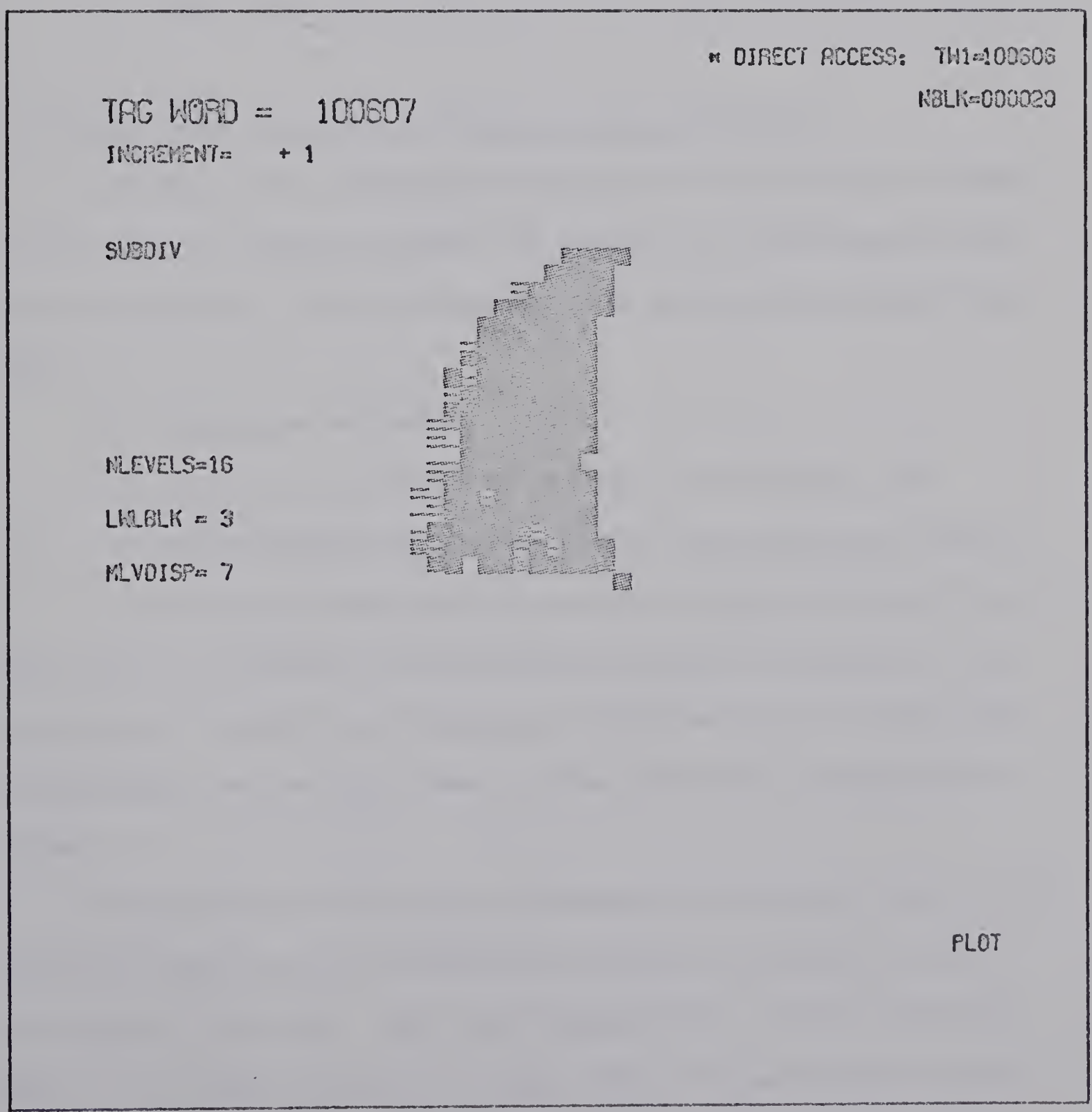


Figure 5.4 Display of the radioisotope distribution in the right lung.



CHAPTER VI

ERRORS ASSOCIATED WITH RADIOISOTOPE IMAGING METHODS

The sources of error in radioisotope imaging studies can be divided into three main groups:

1) Errors associated with radioisotope assay techniques generally.
2) Errors due to gamma camera performance.
3) Subjective errors introduced in the data reduction process.

6.1 Errors associated with radioisotope assay techniques

The basis of a radioisotope assay is the correspondence between the intensity of emitted radiation and quantity of radioisotope as the source of radiation. This correspondence is influenced by several factors:

a) background radiation,
b) statistical character of the gamma ray emission, and
c) three-dimensional distribution of the radioisotope source.

The energy distribution of the background gamma-radiation is so wide that it is difficult to discriminate against it completely. The occurrence of "events" due to background radiation is quite random and its influence upon the assay result can be reduced by averaging techniques.

The statistical character of the gamma ray emission from a given radiation source can be described by the Poisson distribution as was experimentally verified. This can be explained by a simple stochastic model. For example, denote the average number of gamma photons emitted

per unit of time as λ. Let us divide the interval of observation [0, t] into n subintervals of equal length $\Delta t = t/n$ and assume that in each subinterval:

a) only 0 or 1 emissions occurred,

b) gamma-ray emission in a particular subinterval is independent of any other subinterval,

c) and the probability of gamma-ray emission remains constant.

Thus, we have a large number of independent events with outcome 0 or 1 and with the same probability of "1" equal to $\lambda . \Delta t$. Then, for $\lambda^2/n << 1$, the probability of the emission of k gamma photons in the interval [0, t] is well approximated by $P(k) = \frac{(\lambda t)^k}{k!} \exp(-\lambda t)$ (b).

As described by the Poisson distribution the relevance of this phenomenon increases with decreasing λ. Such sources of error can give rise to a false assessment of areas of high or low radioistope concentration appearing in the final display.

In practical experimental situations a measurement is made of a three-dimensional distribution of radioisotope and we assume that the gamma-ray photons travel undeflected from the point of their emission to the point of their detection. It is obvious that there is some attenuation of the gamma radiation during penetration of the intervening tissue. Consequently error will result from the Photoelectric and Compton interactions taking place in the tissue. These phenomena are discussed in the following section. A rough estimate of the errors resulting from the three-dimensional radioisotope distribution could be obtained by measuring radiation fields at different angles.

6.2 Errors inherent in Gamma-Camera operation

The most sensitive part of the Gamma Camera, as far as decrease of resolution is concerned, is the scintillation crystal and associated photomultiplier array. The sensitivity of individual photomultipliers varies over the area of their photo-cathodes (uniformity problems). Sensitivity changes also arise due to statistical fluctuations in the numbers of emitted photoelectrons in the photomultiplier dynodes (multiplication stages). Current developments in gamma camera technology have substantially decreased the magnitude of these latter sources of error.

The principle of "positional" detection of the incident gamma photons was explained in Chapter I. This "positional" information is influenced by Compton interactions between the incident gamma-ray photons and the atoms of the scintillation crystal.

In the photoelectric interaction the whole energy of the gamma photon is transferred, as kinetic energy, to an electron which is then expelled from its orbit and becomes a photoelectron. The characteristic x-ray produced by the emission of this orbital electron has a high probability for absorption in the crystal resulting in a light output proportional to the total absorbed gamma-ray photon energy.

In the energy range 100 keV to 500 keV with a one-half inch thick NaI(Tl) crystal, approximately 30% of the incoming gamma photons undergo Compton scattering. In such a process the gamma photons lose energy by interactions with the atomic electrons and are deflected by an angle of up to $\pm\pi$ from their original direction. The resulting angles and corresponding energy of the degenerated photons follow a distribution given by the Compton energy-angle relationship. Details concerning these phenomena can be found in (5).

The resolution loss due to the Compton effect can be minimized by rejection of the scattered radiation by proper (electronic) energy discrimination.

The choice of energy discriminator levels is a rather complex problem, depending as it does upon the energy of the radioisotope used, the particular clinical situation and design parameters of the camera. In particular the collimator contributes considerably to resolution loss via the Compton scattering mechanism.

6.3 Subjective errors arising from the data reduction process

To generalize the approach to subjective errors arising in the data reduction process is rather difficult. Let us consider as examples the two experiments described previously. In these cases sources of subjective error can be either incorrect boundary definition or incorrect interpretation of the graphs resulting from the series integration and consequent erroneous specification of the significant matrix range for final integration.

Such errors depend to a great extent upon:

a) the operator's previous knowledge of the data being processed,

b) knowledge of the clinical situation during data collection,

and c) familiarity of the operator with the graphical representation of the data used.

To minimize the possibility of erroneous data interpretation different graphical representations should be used for different experimental applications. The representation described in Section 4.2 is most suited to cases where the boundary or subdivision definition require only a few ranges of the radiation intensity to be distinguished on the

screen. (In applications where display of a higher number of ranges is required then rapid increase in vector density would cause considerable problems.) The appropriate selection of these ranges, however, by the specification of Display Parameters, is of great importance. This was shown in Figures 4.2.3.3 - 8. One method which would facilitate the Display Parameter specification is outlined in the following chapter. This method is based on the display of the graph of function w(x, y) for points (x, y) from the straight line specified by the light pen on the two-dimensional representation.

For all cases an operator who is familiar with the experimental techniques and nature of the data is required for optimum results.

CHAPTER VII

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

The data reduction subroutines which have been developed satisfy the common requirements of the three experiments described in Chapter II. Because of the general character of these requirements, and corresponding functions implemented, the evaluation of data from all experimental applications of the gamma-ray camera is possible. It is expected, however, that the user will provide his own particular routines for incorporation in the system as presently developed. These routines would allow for example specific numerical procedures, either on the matrices created in the working space or directly upon the experimental data, using graphics derived information relating to the area of interest on a matrix or to the range of interest in the series. The numerical evaluation of data with the present system is restricted to procedures which are of general use. The integration and averaging routines fall into this category.

The graphical representation of a radioisotope distribution as developed in this thesis satisfied the general experimental data reduction requirements. However, other methods of two dimensional representation should be implemented. One possible technique was outlined in Section 4.2.3. Available also are a number of routines for plotting of isocontour maps which could be easily modified for use with GRID.

As far as three-dimensional representation of the function $w(x,y)$ is concerned probably the easiest and most practical method would be the display of the graph of function $w(x, y)$ for points (x, y) from the straight line specified by the light pen on the two-dimensional

representation. Such a technique would involve a polynomial or spline approximation of function the w(x, y) using the function values at the crossections of the specified line with the horizontal and vertical lines of the grid [i, j]. The computation of these function values using the matrix elements w[i,j] would involve formulae derived from a Taylor expansion of the function w(x, y) in both the x and y directions. The display of such graphs for one or more different lines would give the operator more information necessary for the appropriate specification of the Display Parameters.

Future research should be directed also towards the development of methods which would present the actual three-dimensional distribution of radioisotope based upon measurements of gamma radiation from the different sides of the object. The elimination of errors due to the attenuation of gamma radiation during penetration of the intervening tissue could be attempted.

The use of a digital computer for evaluation of gamma-ray camera output data is necessitated by the large amount of data produced during normal experimental use. The Interactive Graphics device has obvious advantages when the data to be processed represents a three-dimensional function of radioisotope distribution and a relatively low accuracy of evaluation is satisfactory. Presentation of data in the form of pictures or graphs has its place in medical diagnosis and it is expected that the graphics software systems, developed for particular applications, will allow evaluation of experimental data at the graphics terminal by the Clinician himself.

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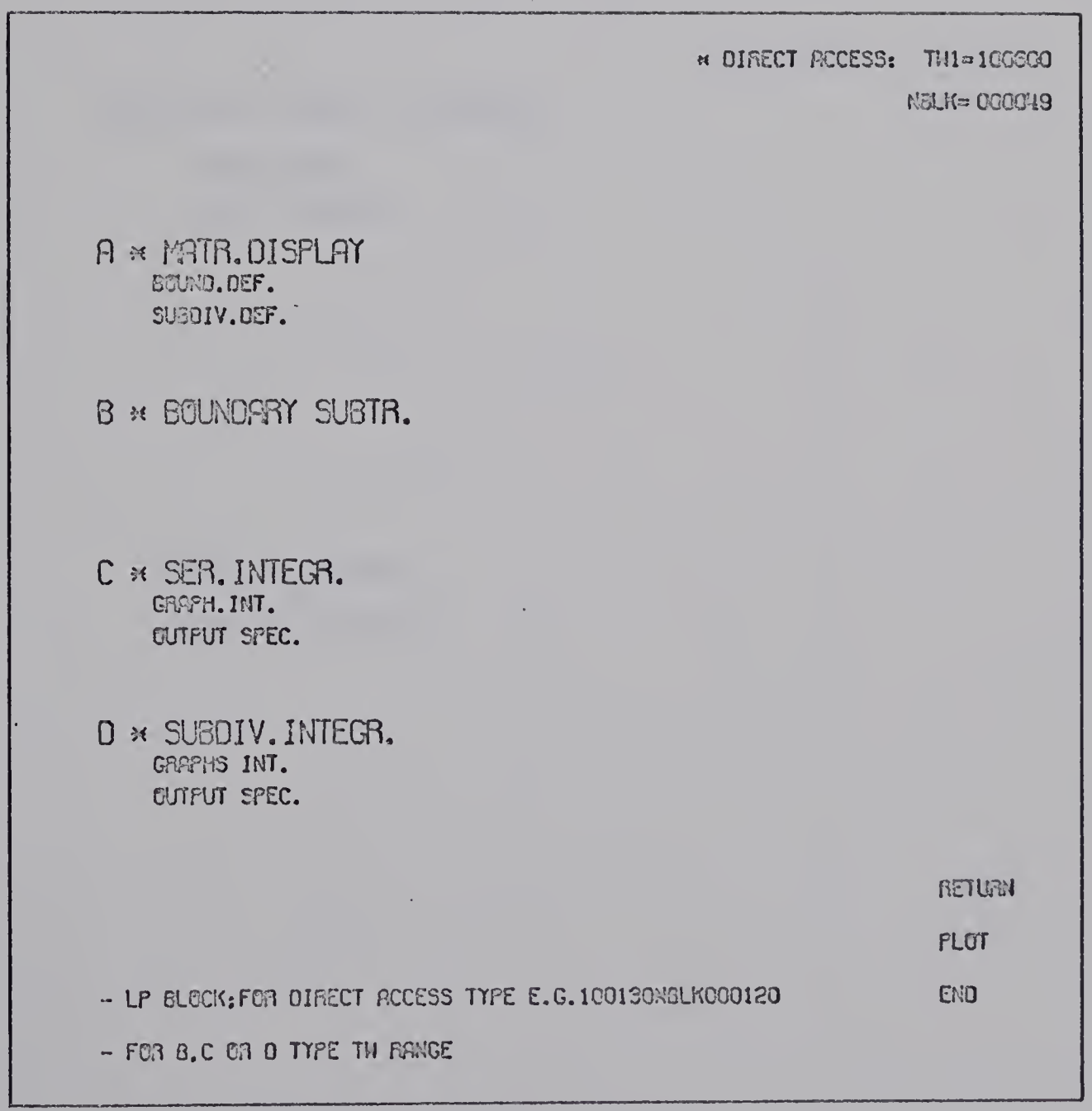
A P P E N D I X

Figure A.1 Decision Table



PLOT 1 12 JULY 1970

Figure A.2 Boundary Options Table

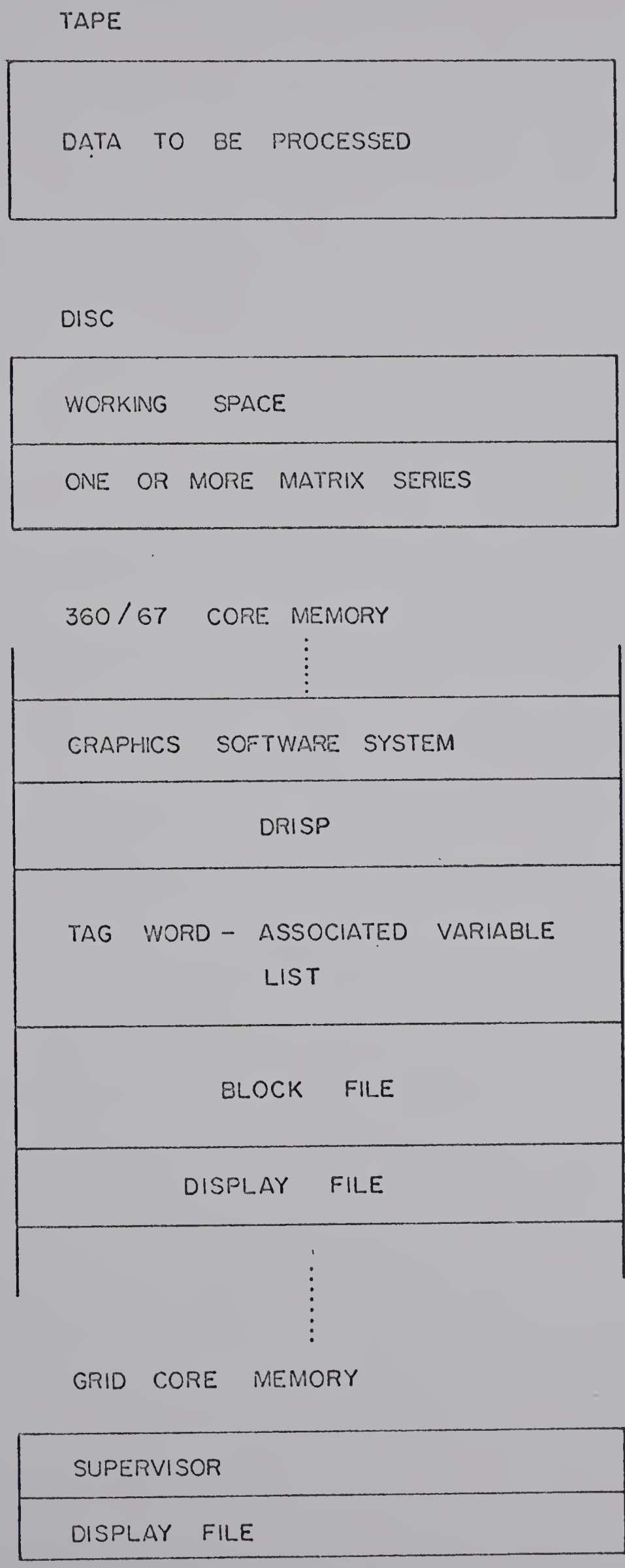
```
                                        «DIRECT ACCESS:  TH1=100600
                                                         NBLK=000049
TAG WORD =100601 TO 100648

    «STORE AREA:
     SAV= 000001


«INTEGR.IN   «ZERO IN
«INTEGR.OUT  «ZERO OUT


                                                         RETURN
                                                         PLOT
```

PLOT 2 12 JULY 1970


TAPE
DATA TO BE PROCESSED
DISC
WORKING SPACE
ONE OR MORE MATRIX SERIES
360/67 CORE MEMORY
GRAPHICS SOFTWARE SYSTEM
DRISP
TAG WORD - ASSOCIATED VARIABLE LIST
BLOCK FILE
DISPLAY FILE
GRID CORE MEMORY
SUPERVISOR
DISPLAY FILE